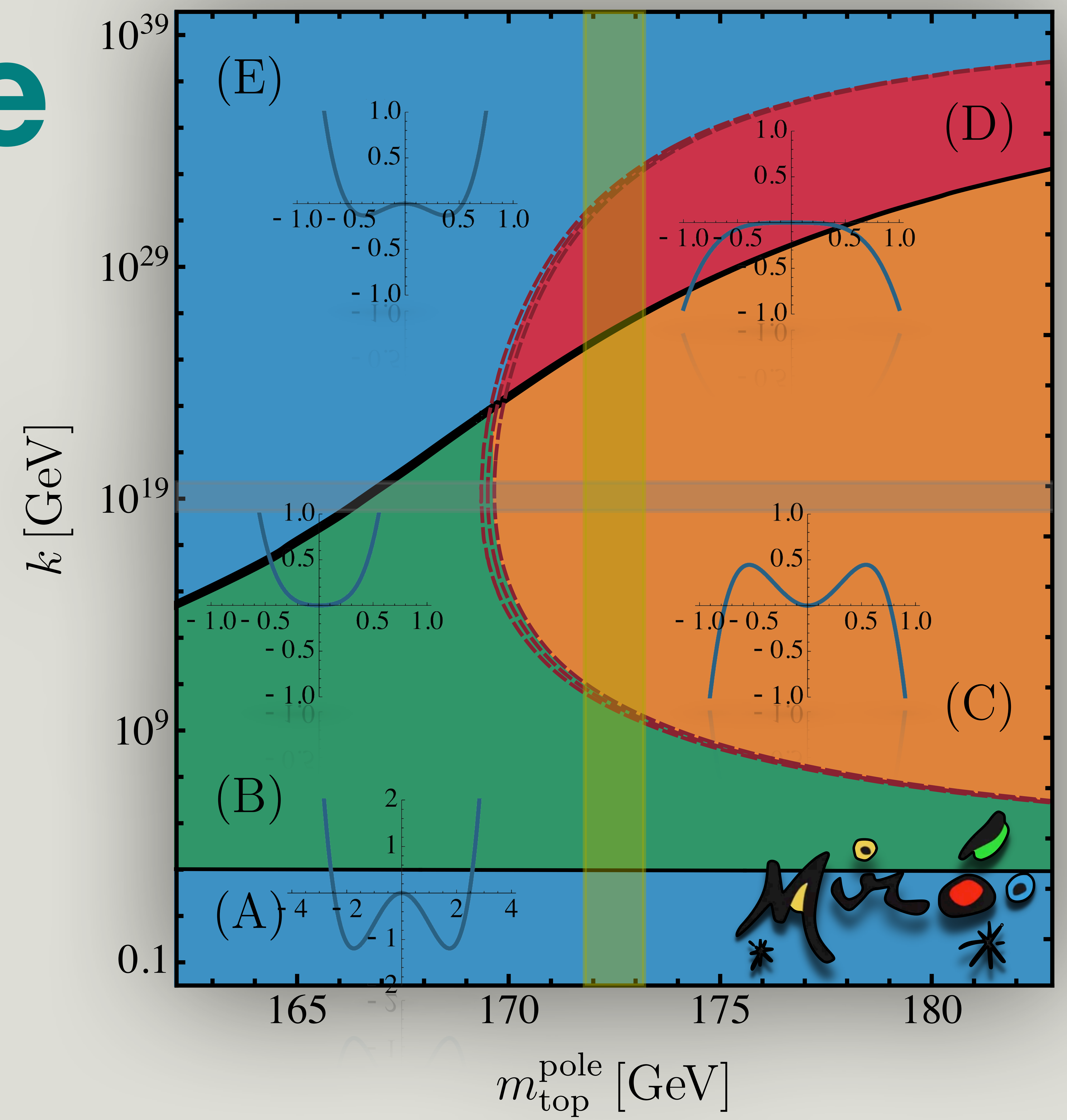
New phases of the Standard Model Higgs potential

UV Complete QFTs for Particle Physics

4.9.2023 San Miniato

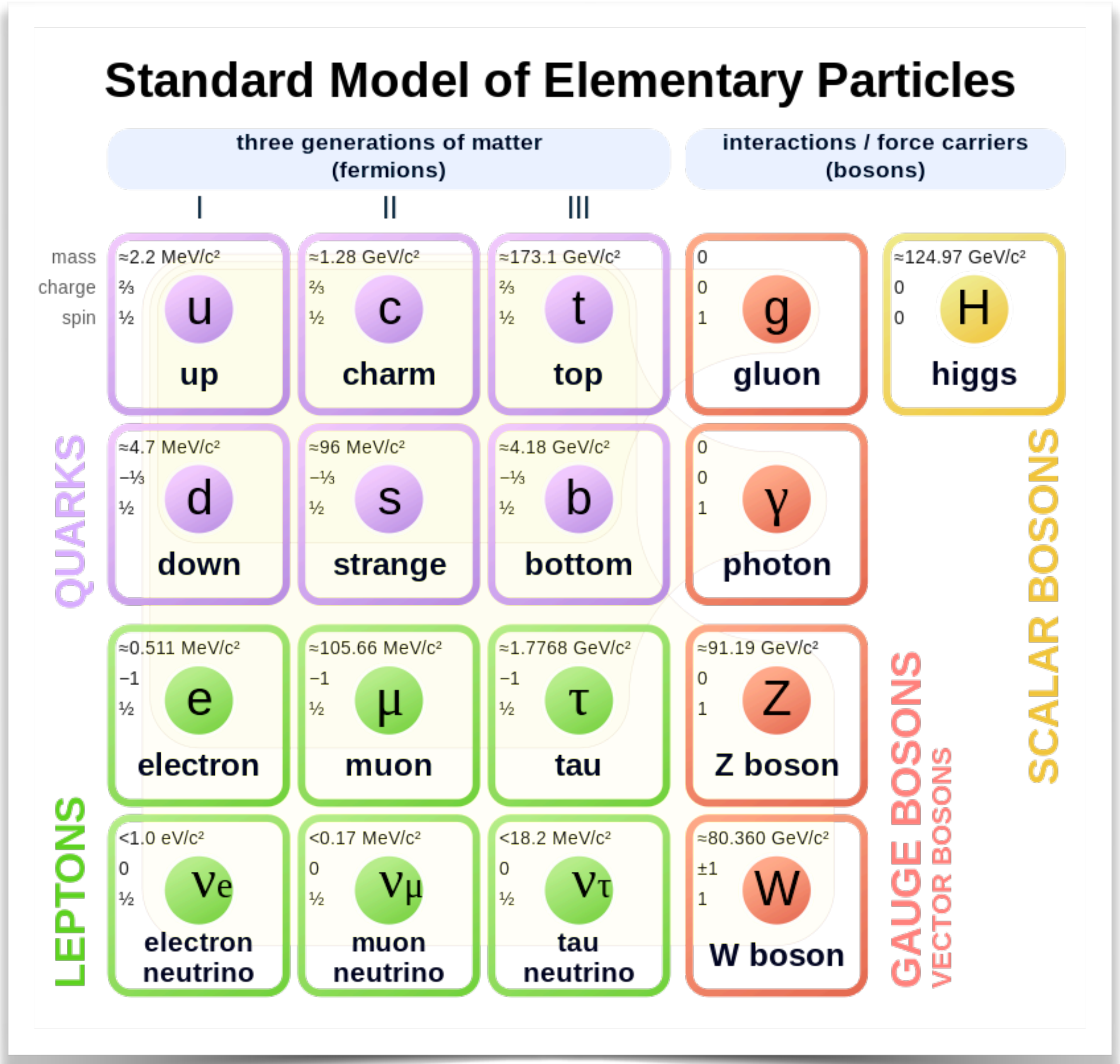
Álvaro Pastor Gutiérrez

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



Based on 2308.13594 with Florian Goertz

Today's picture of high energy physics



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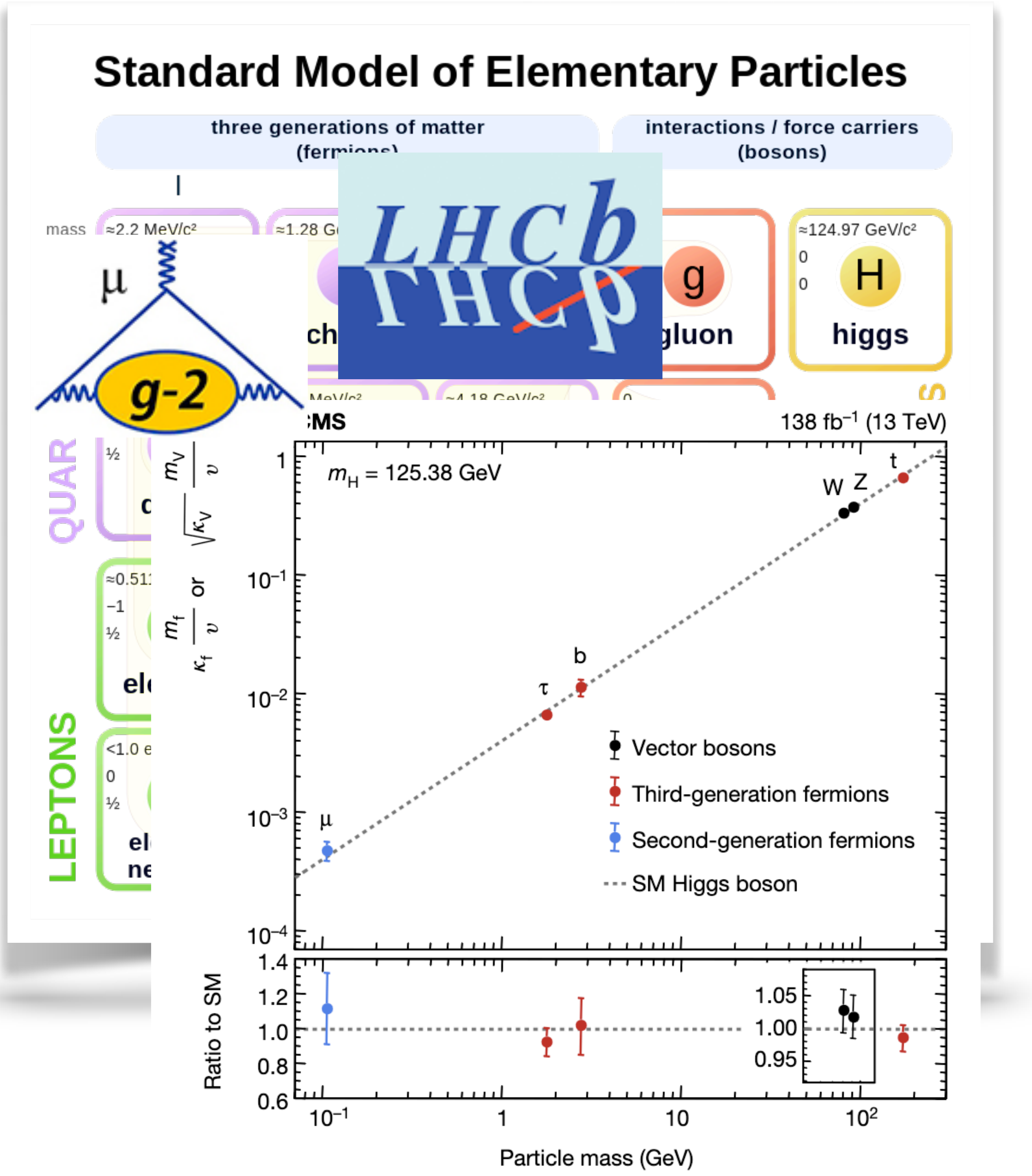

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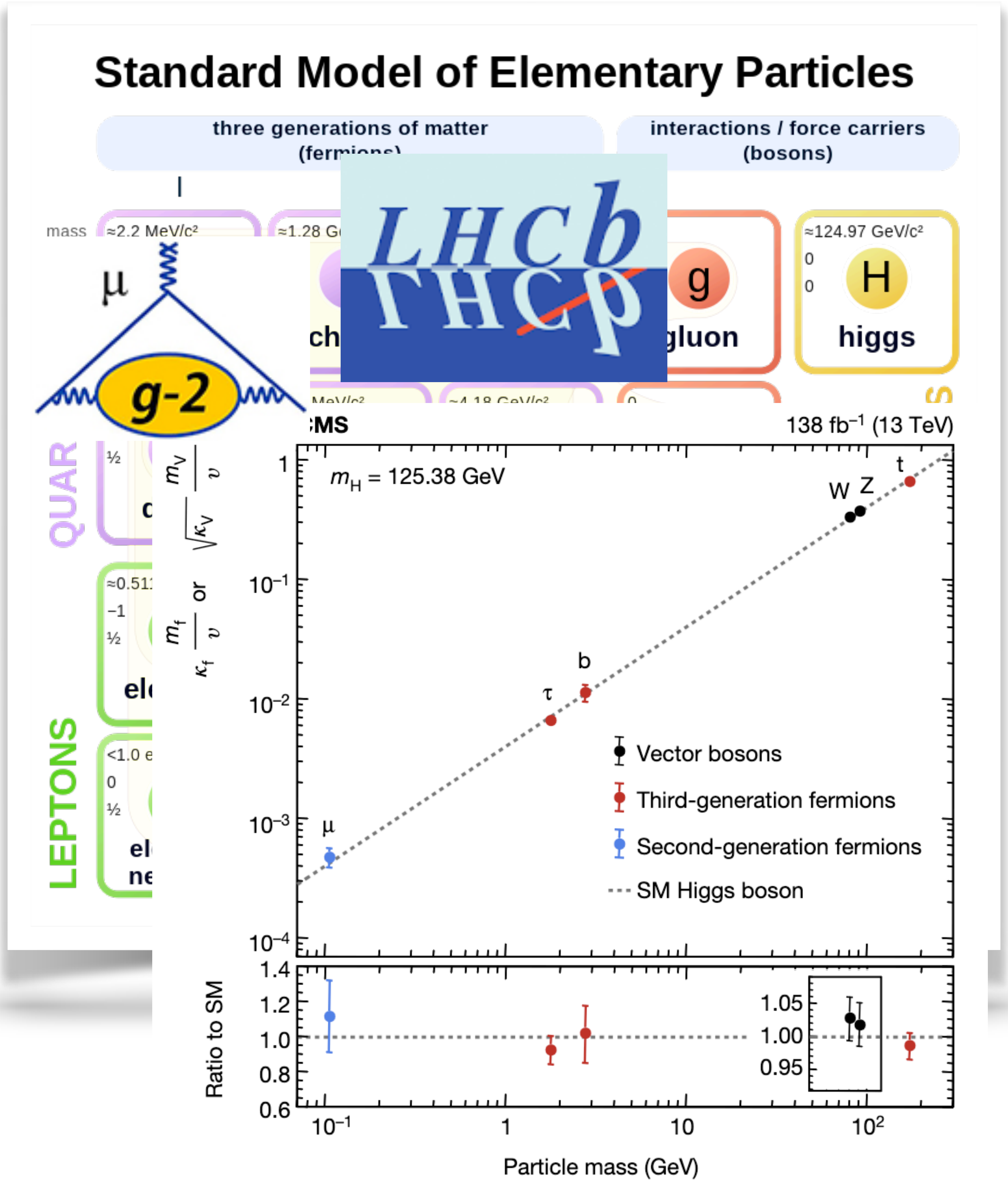
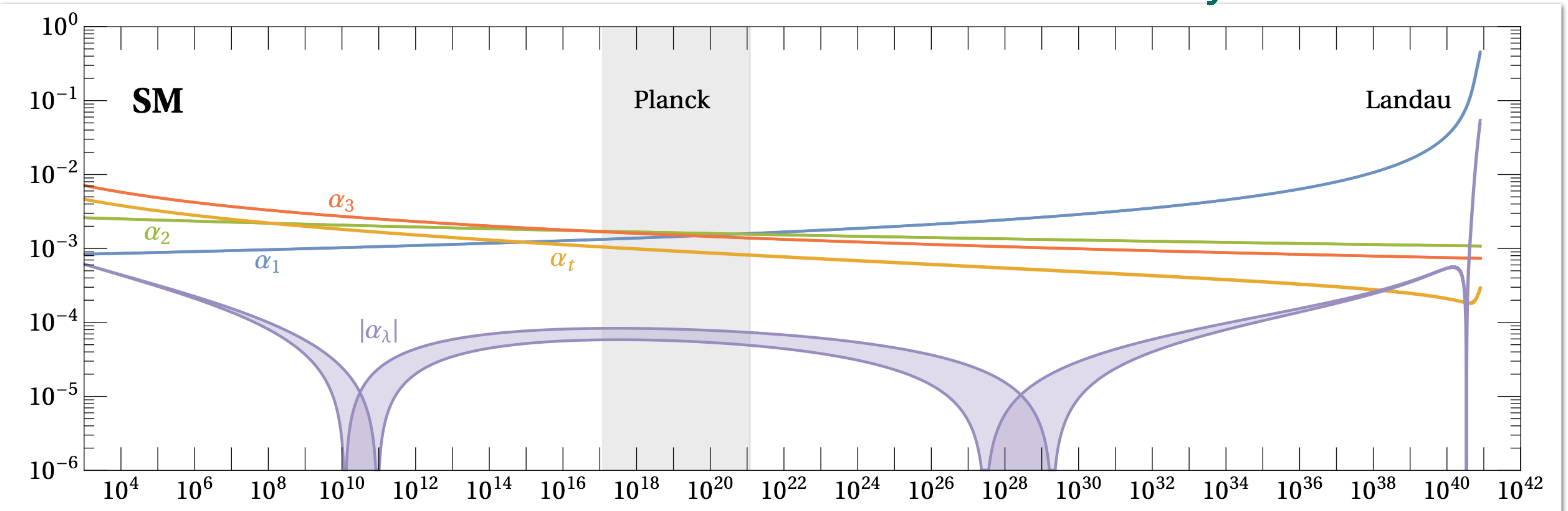


Is the Standard Model the fundamental theory of nature?



Hiller,Höhne,Litim,Steudner’22

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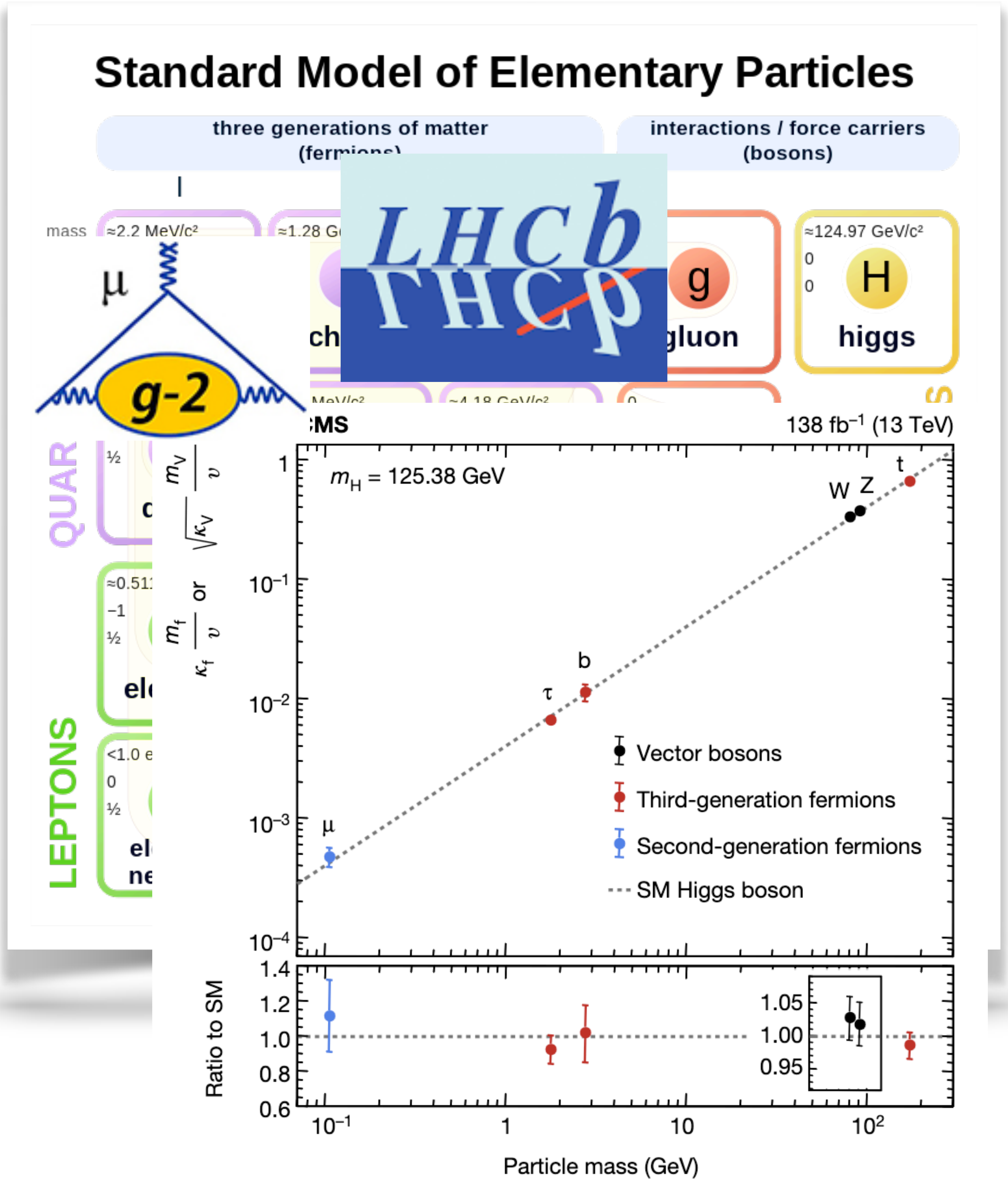

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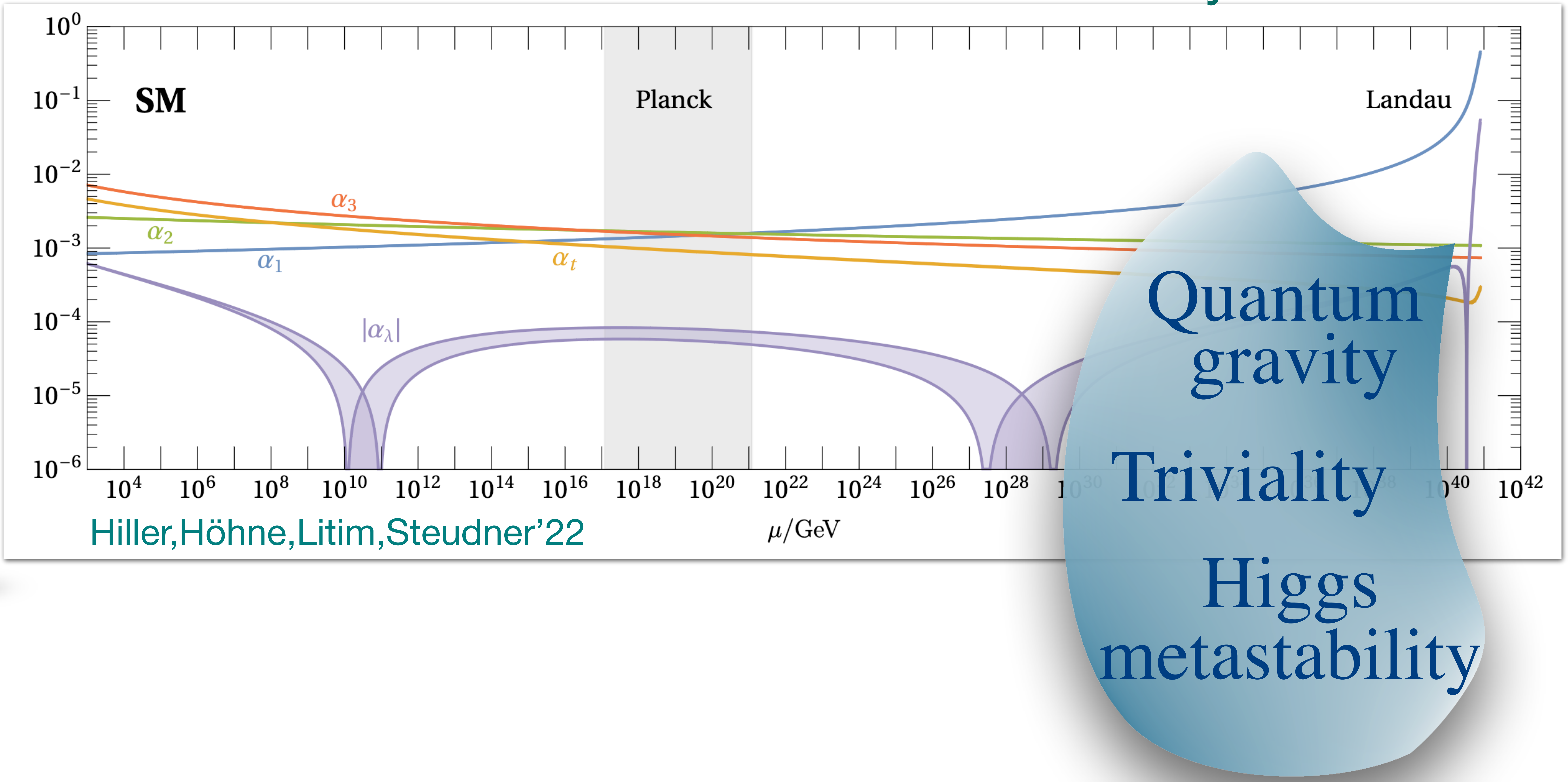

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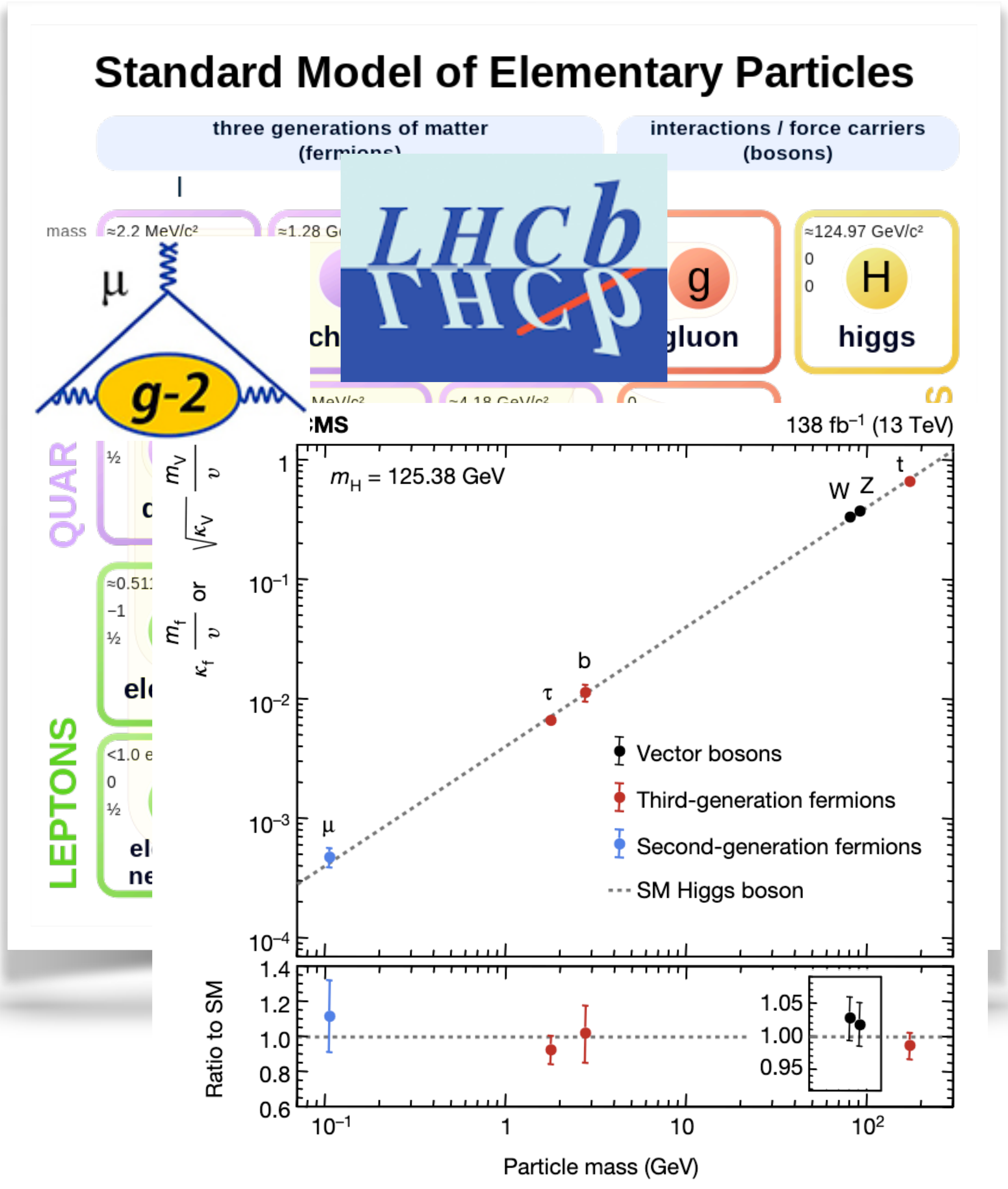

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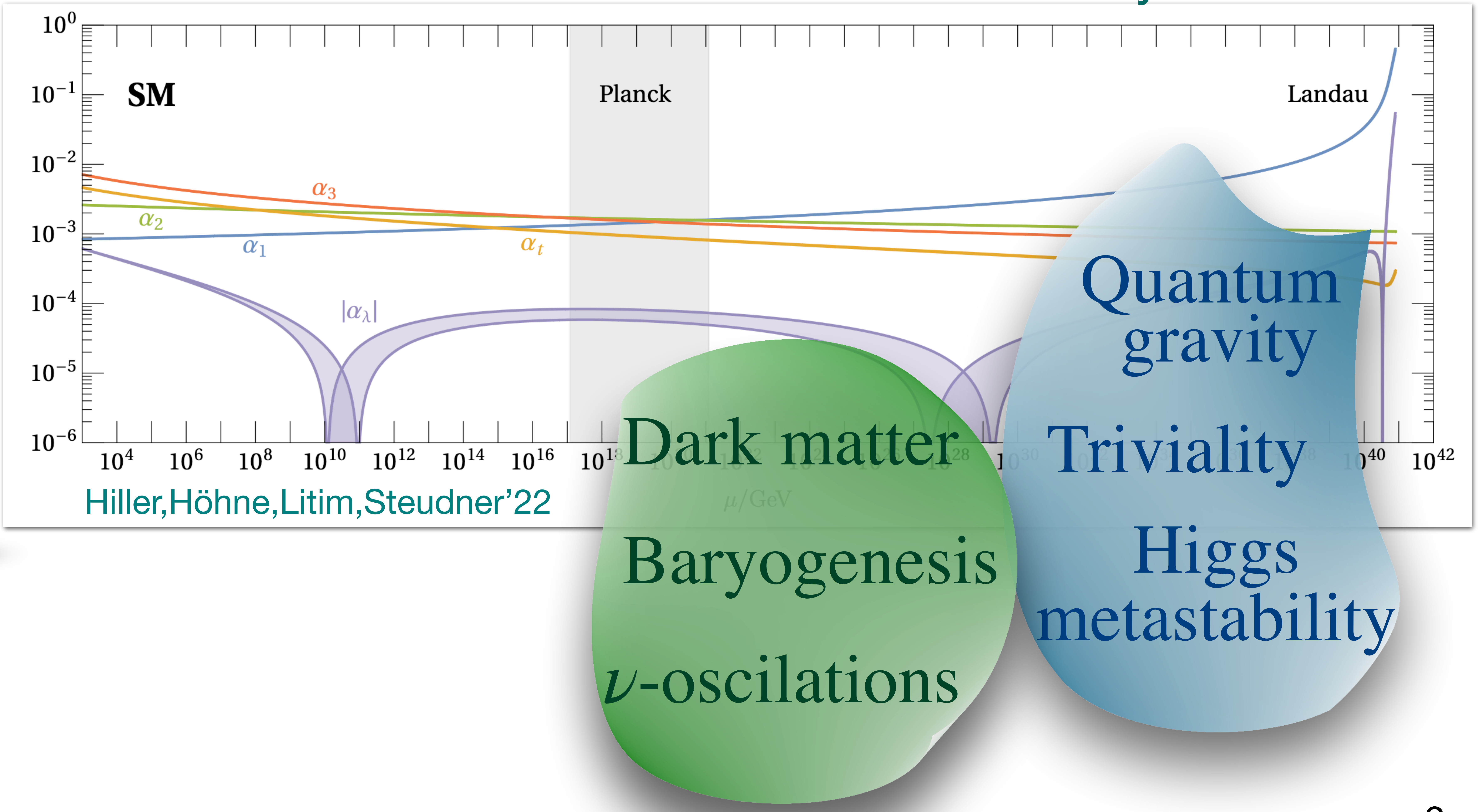

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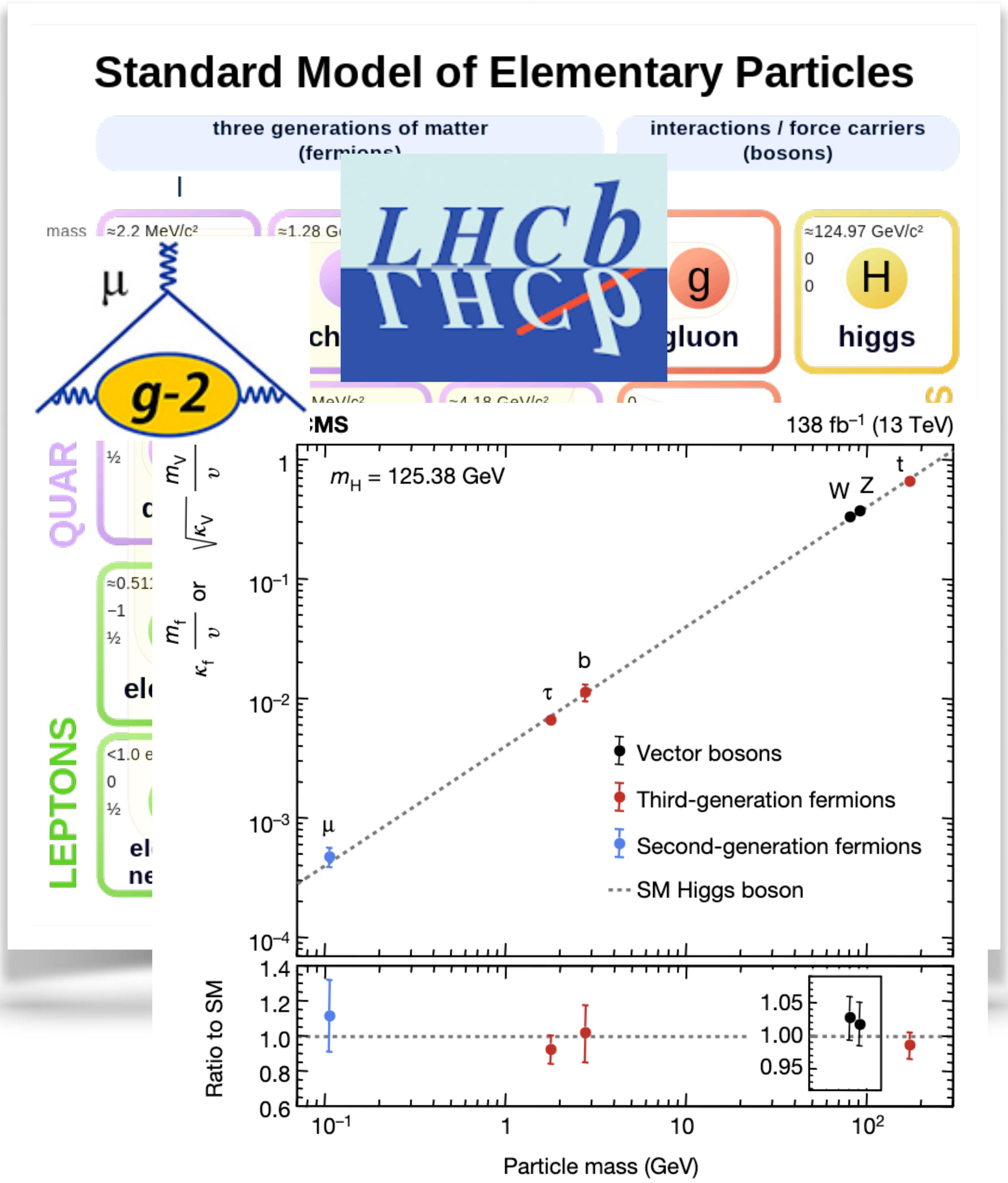

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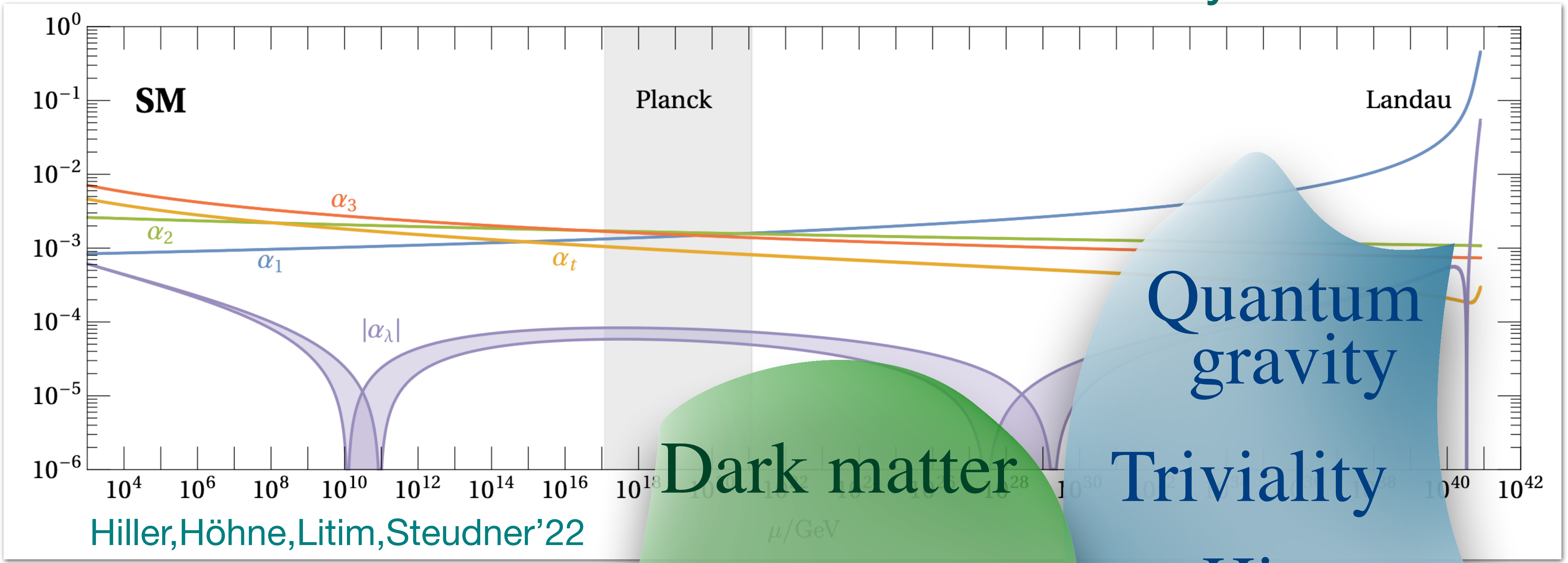


No, but close…

Dark matter

Baryogenesis

ν-oscilations

Quantum gravity

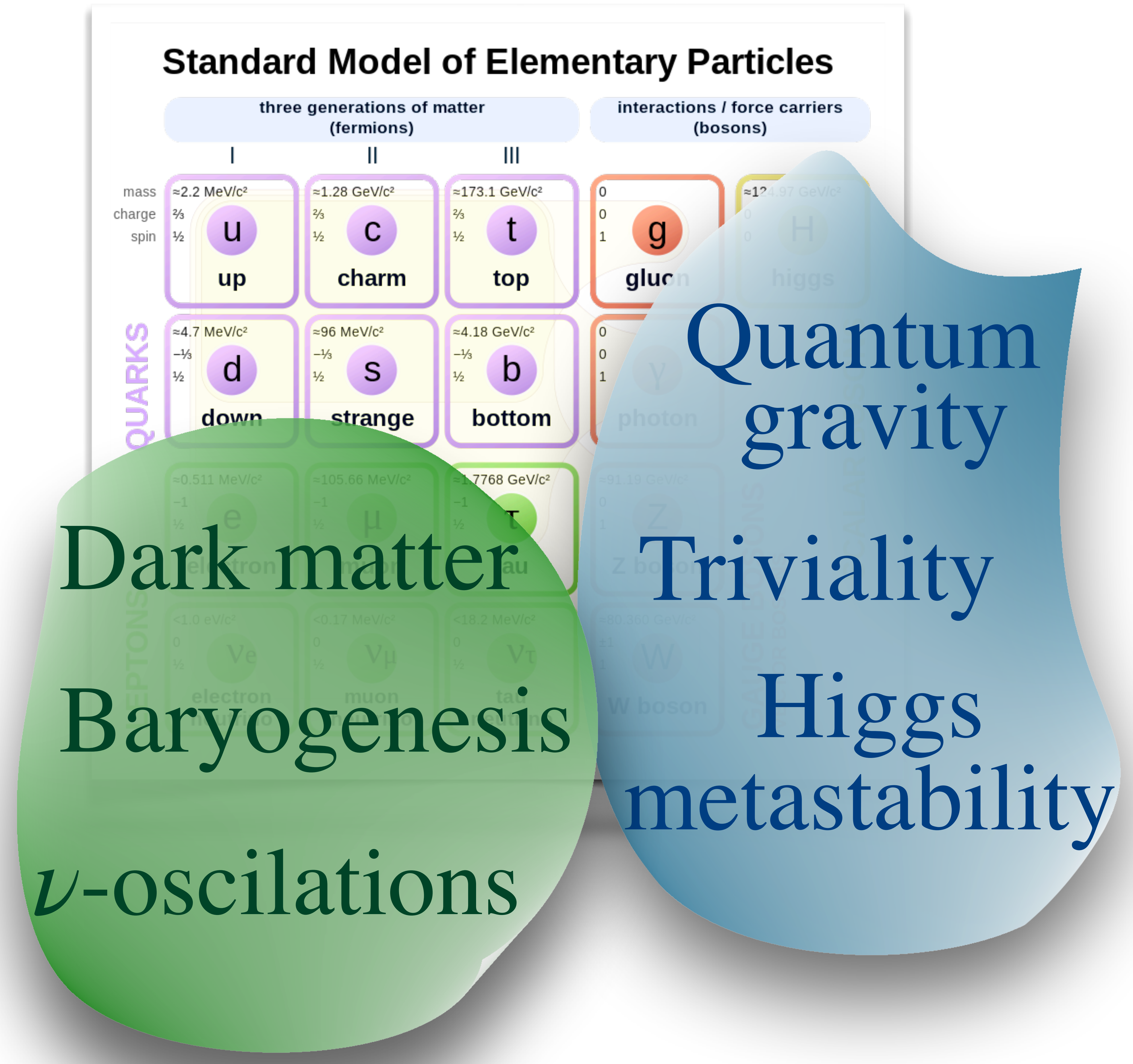
Triviality

Higgs metastability

A "fresh" look at the Standard Model

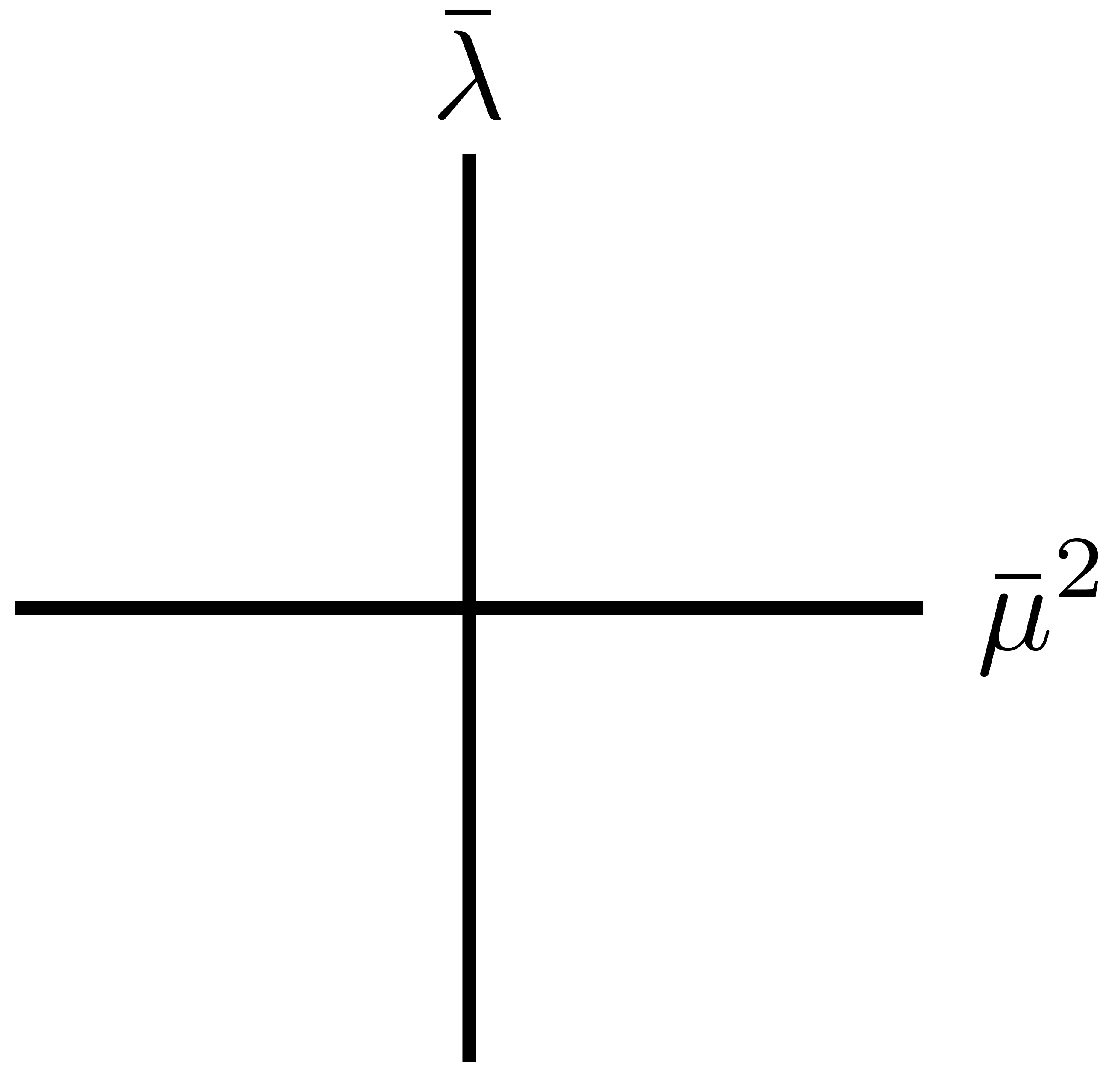
- **Revisit** the SM **Higgs sector** employing **non-standard** but **old** RG tools.

- **New phases** relevant for addressing the high energy **phase structure of the SM with and without new physics.**
- Can the SM or SM-like theories be formulated in a **UV complete manner**?



Higgs potential and curvature mass

$$u(\bar{\rho}) = V_{\text{eff}}(\rho)\,/\,k^4 = \bar{\mu}^2\bar{\rho} + \bar{\lambda}\bar{\rho}^2 \qquad \bar{\rho} = Z_\Phi \frac{\text{tr}\,\Phi^\dagger\Phi}{k^2} \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathcal{G}_1 + i\mathcal{G}_2 \\ H + i\mathcal{G}_3 \end{pmatrix}$$



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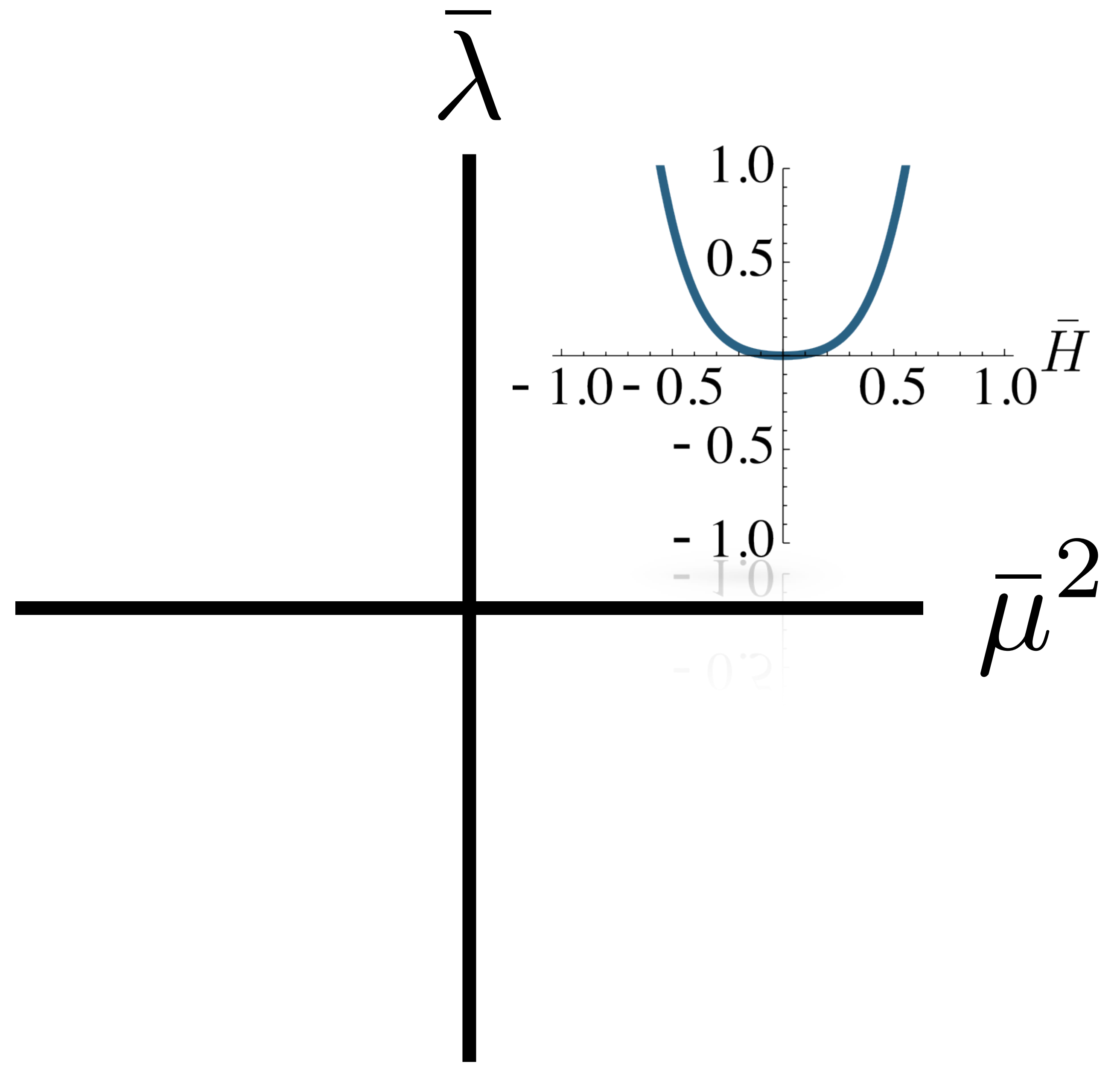

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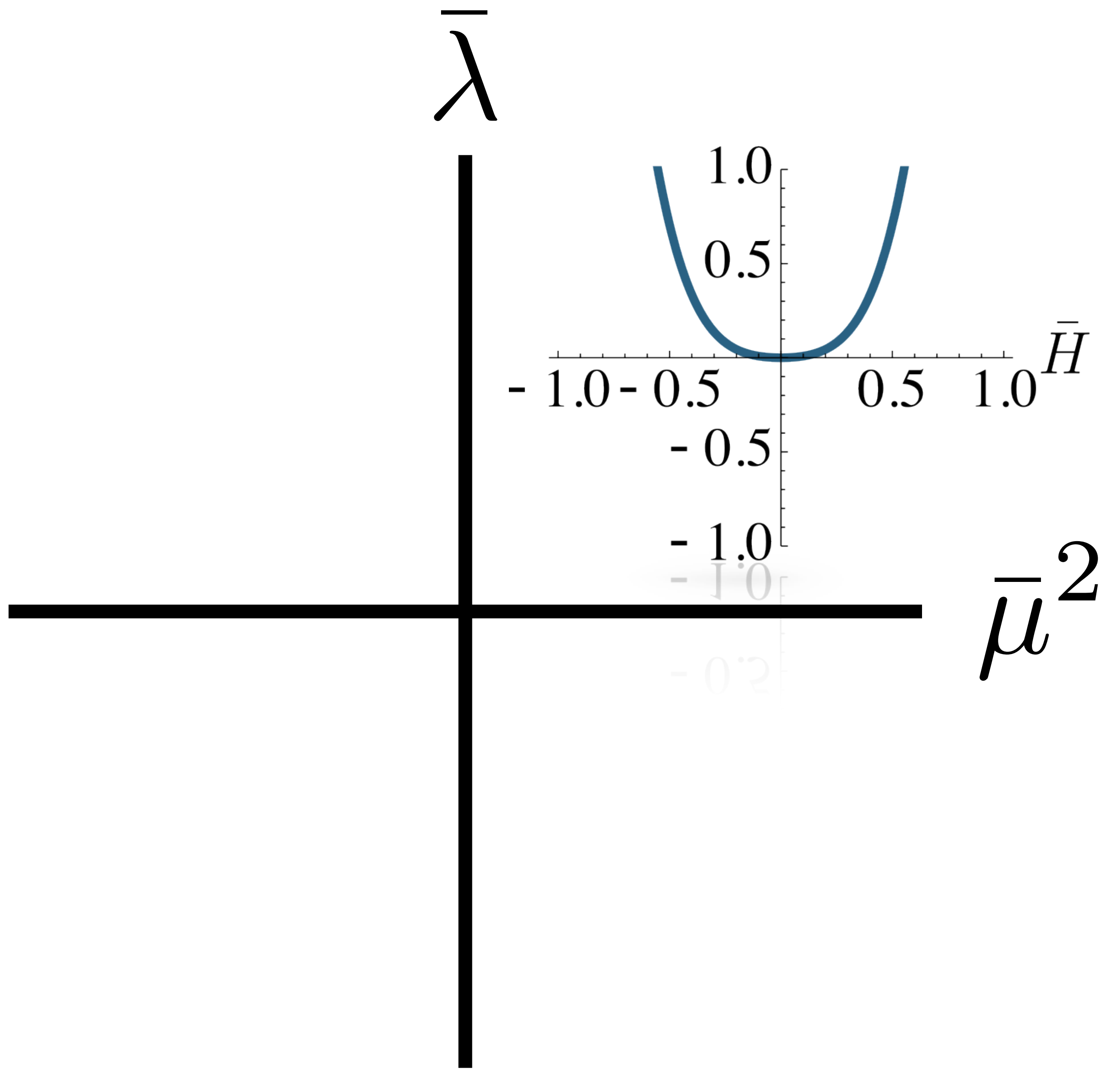
Spontaneous Symmetry Breaking:

$$\partial_\rho u(\bar{\rho})\big|_{\bar{\rho}_0} = 0 \rightarrow \bar{\rho}_0 = \frac{\bar{v}^2}{2} = \frac{-\bar{\mu}^2}{2\,\bar{\lambda}} \geq 0 \rightarrow \bar{m}_H = \sqrt{2\bar{\lambda}}\,\bar{v}$$



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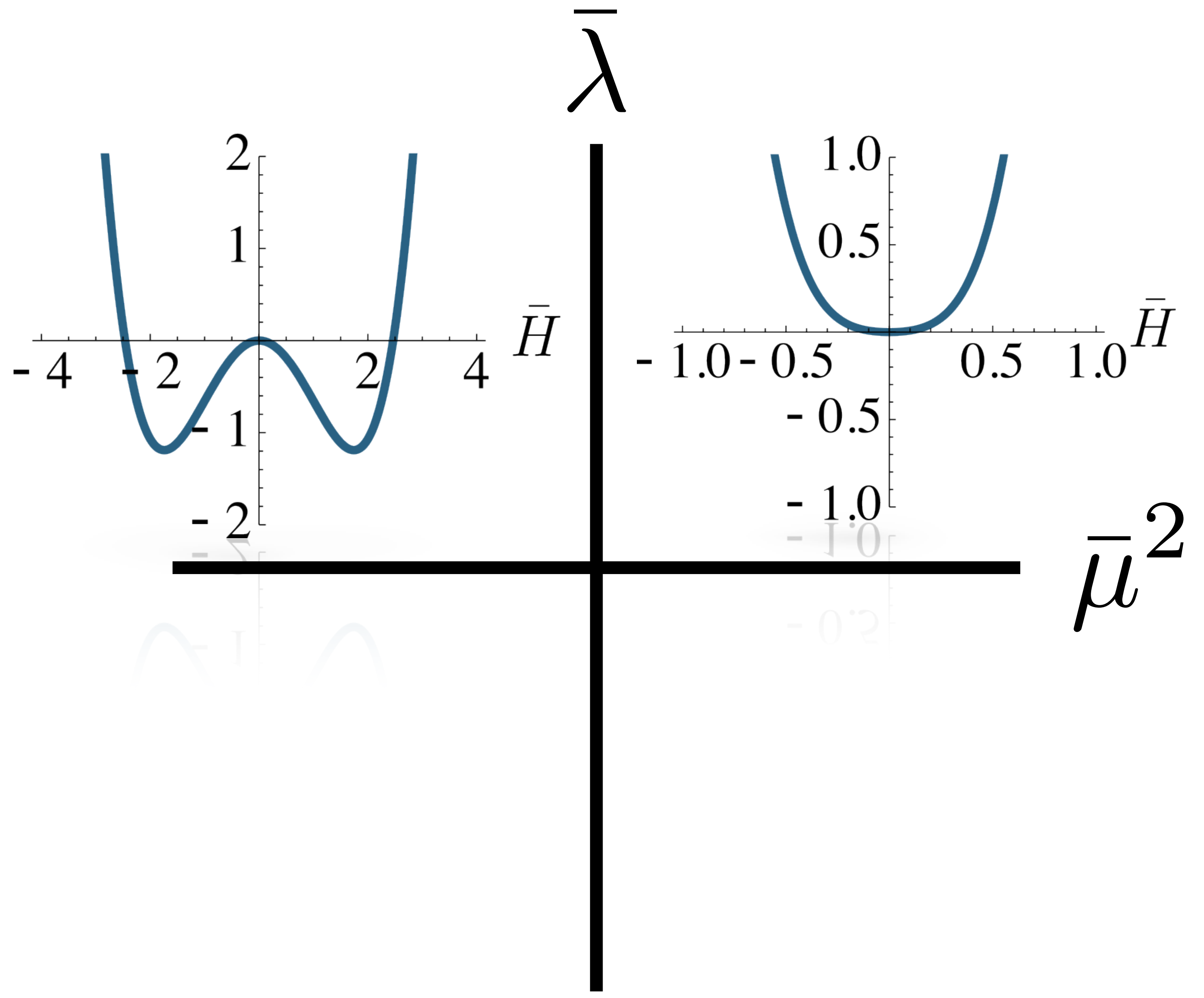

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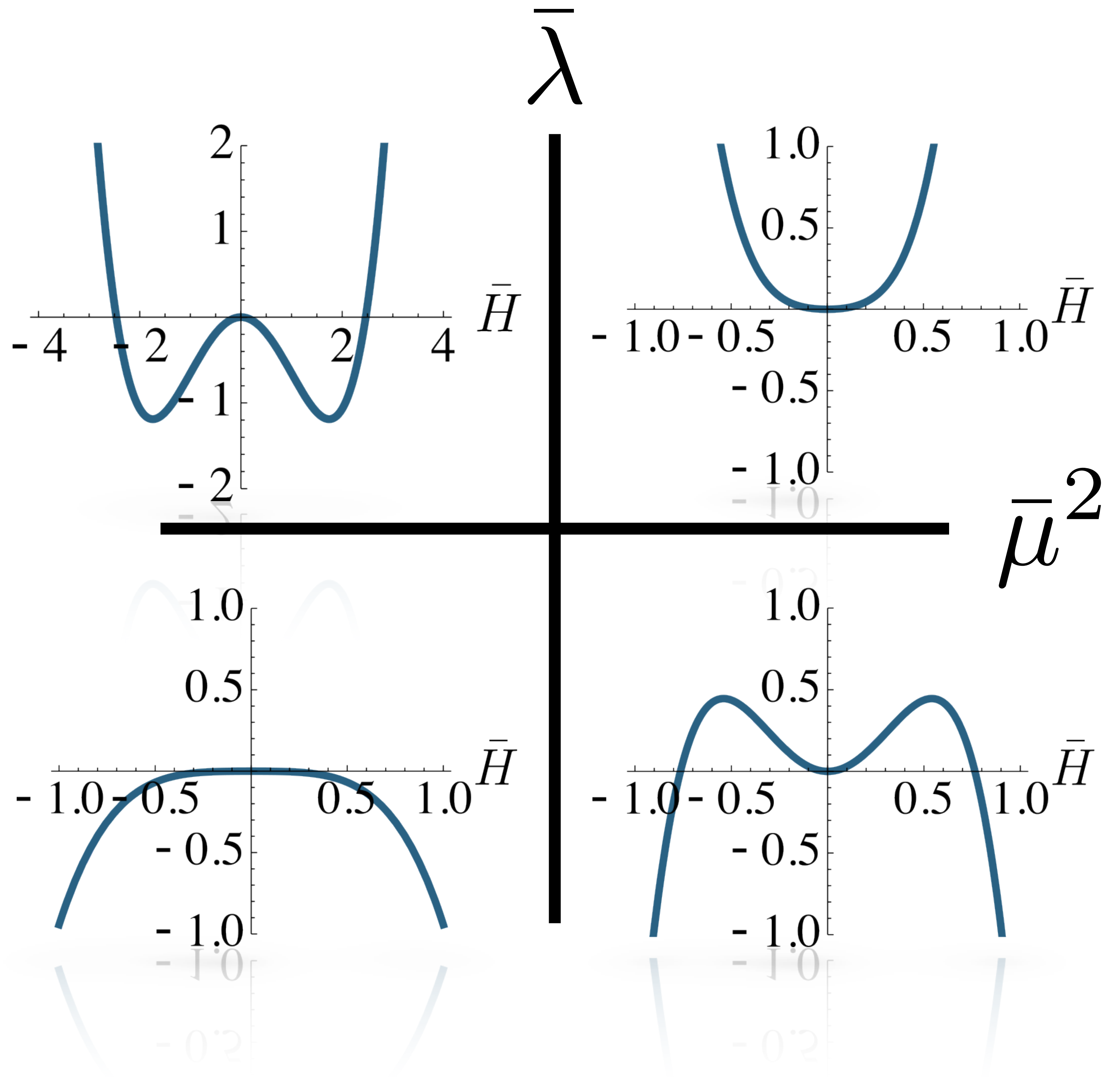

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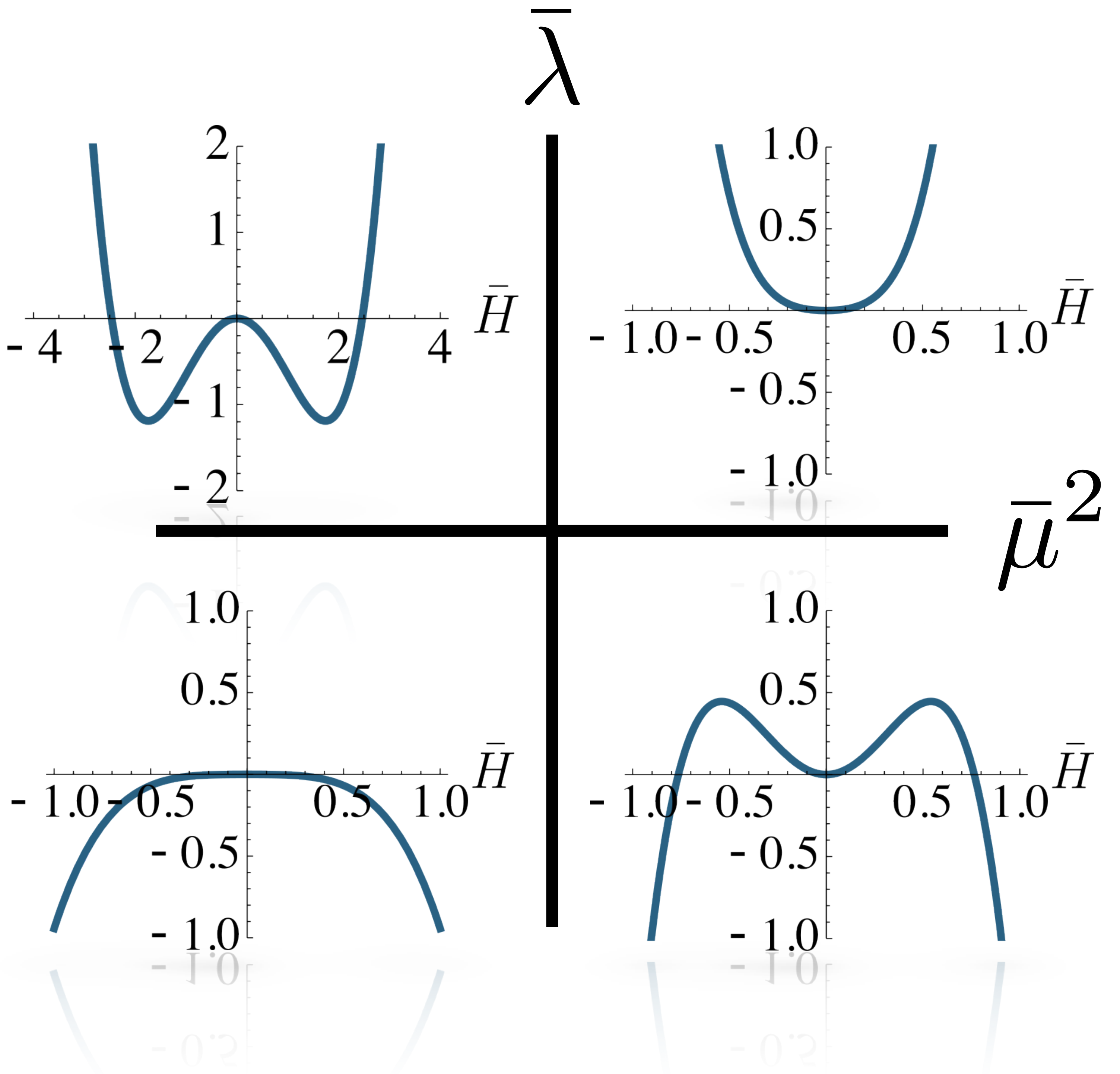

Energy scale evolution: $\partial_t \equiv k\,\partial_k$

$$\begin{cases}\partial_t\,\bar\mu^2 = \partial_t\left(\partial_{\bar\rho}u(\bar\rho)\right) = (-2+\eta_\Phi)\,\bar\mu^2 + \partial_{\bar\rho}\,\left[(\partial_t V_{\rm eff}(\rho))/k^4\right]\\ \partial_t\bar\lambda = \partial_t(\partial_{\bar\rho}^2\,u(\bar\rho)) = 2\,\eta_\Phi\bar\lambda + \frac{1}{2}\partial_{\bar\rho}^2\,\left[(\partial_t V_{\rm eff}(\rho))/k^4\right]\end{cases}$$

Functional Renormalisation group

$$\Delta S_k[\phi] = \int_p \phi(p) R_k \phi(-p)$$

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi]$$

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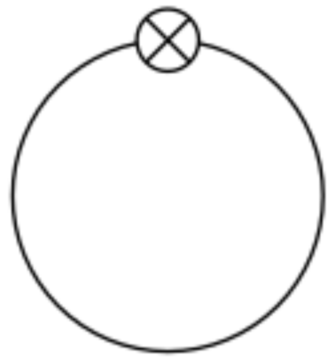
$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\left[\frac{1}{\Gamma_k^{(2)} + R_k}\partial_t R_k\right] = \frac{1}{2}$$ 

Wetterich '93

- One loop exact
- Non-perturbative
- Mass-dependent RG
- Analytic regulators
- Systematically improvable truncations

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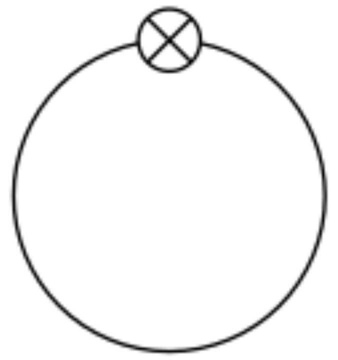

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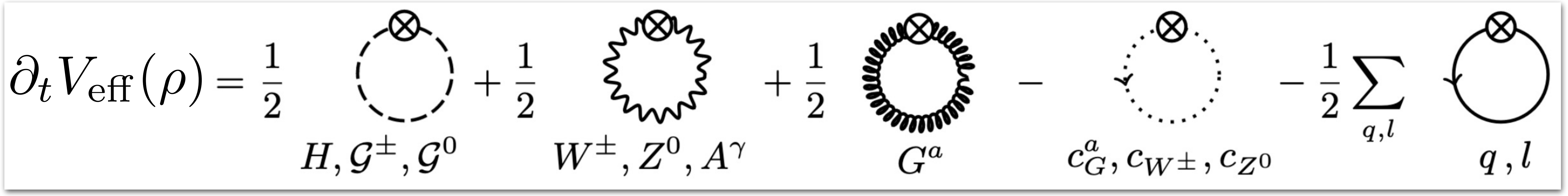
Track shape of the potential along the RG-scale

$$\begin{cases} \partial_t\, \bar{\mu}^2 = \partial_t\left(\partial_{\bar\rho} u(\bar\rho)\right) \\ \partial_t \bar\lambda = \partial_t(\partial^2_{\bar\rho}\, u(\bar\rho)) \end{cases}$$



Gies,Gneiting,Sondenheimer '14 Borchardt,Gies,Sondenheimer '16 Sondenheimer '17 Gies,Rechenberger,Scherer,Zambelli '13 Gies,Zambelli '15'16 Gies,Sondenheimer'19 Gies,Sondenheimer,Ugolotti,Zambelli'18'19 APG,Pawlowski,Reichert'22

(A) $k = 100$ GeV
$u(\bar{\rho})$
(B) $k = 10^4$ GeV
$u(\bar{\rho}) \times 10^2$
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$\bar{H}$
$k_{\text{SSB},1}$
k_{meta}
k_{Planck}
k_{inst}
$k_{\text{SSB},2}$
g_3
y_t
g_2
g_1
y_b
$\bar{\lambda}$
$10 \times \bar{\mu}^2$
(A)
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(C)
(D)
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No well defined **ground state**
Electroweak **vacuum decay lifetime** ruled out
Unviable phase evolution

- Polynomial potential: $u(\bar\rho) = \bar\mu^2\bar\rho + \bar\lambda\bar\rho^2$
  - ➡ **No access** to global properties of the Higgs potential

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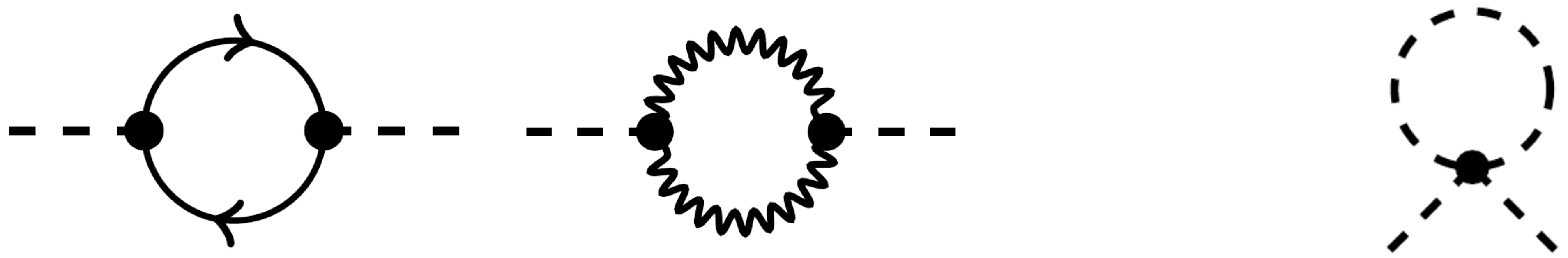
$$\partial_{\bar{\rho}} \, \overline{\text{Flow}} \left[V_{\text{eff}} \right] \supset \frac{3 \, y_t^2}{8 \, \pi^2} - \frac{9 \left(g_1^2 + 5 \, g_2^2 \right)}{320 \, \pi^2} - \frac{3 \bar{\lambda}}{8 \, \pi^2 (1 + \bar{\mu}^2)}$$



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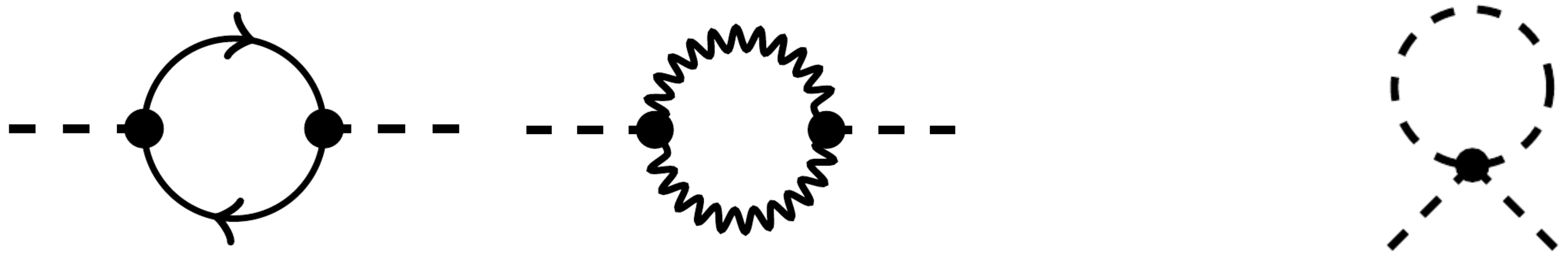

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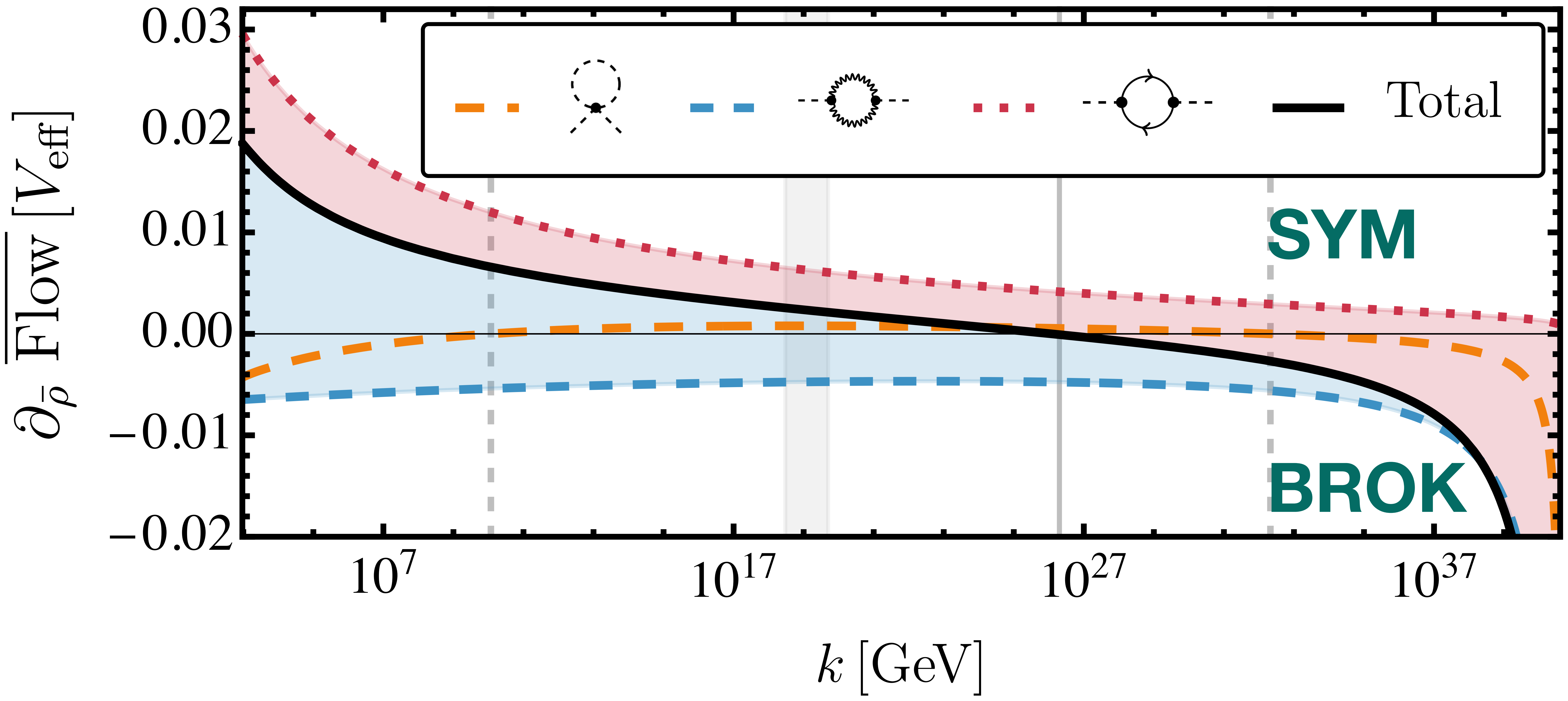

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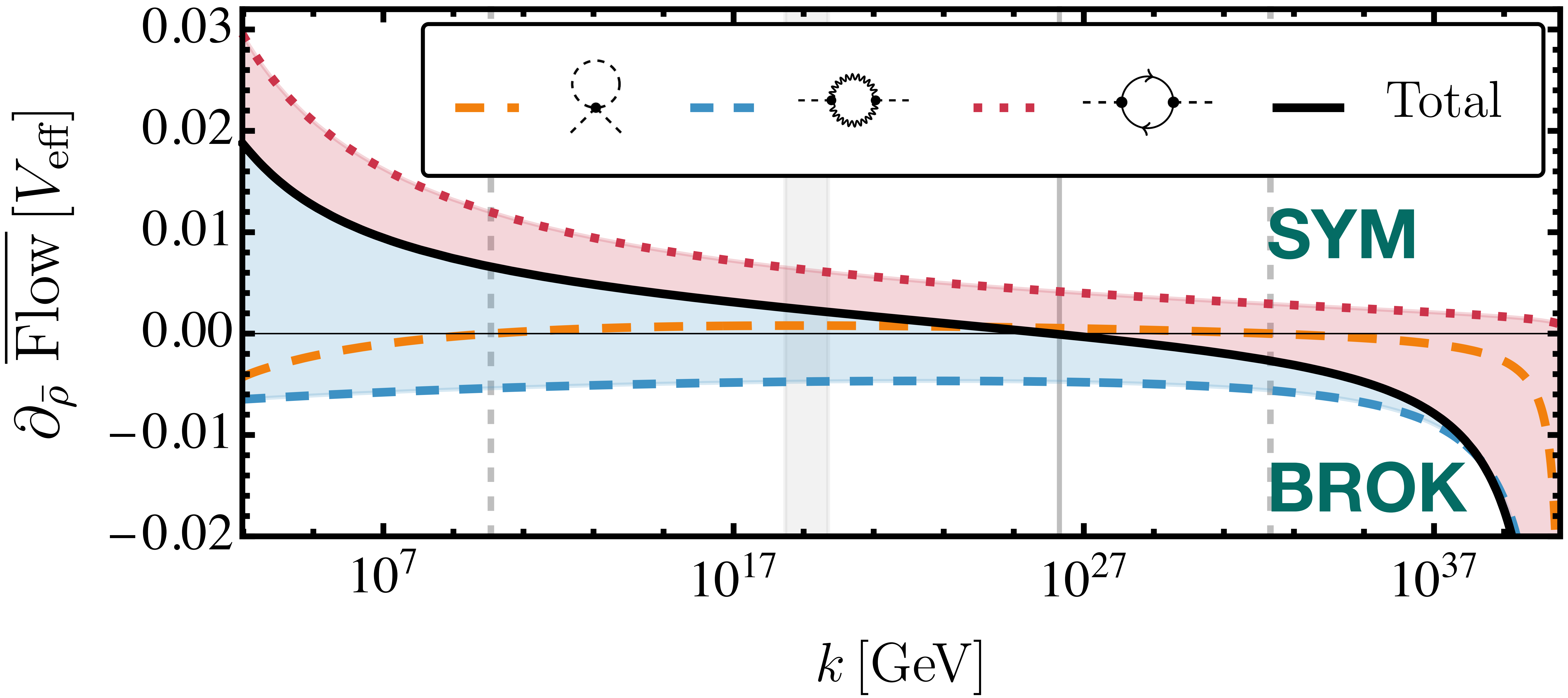
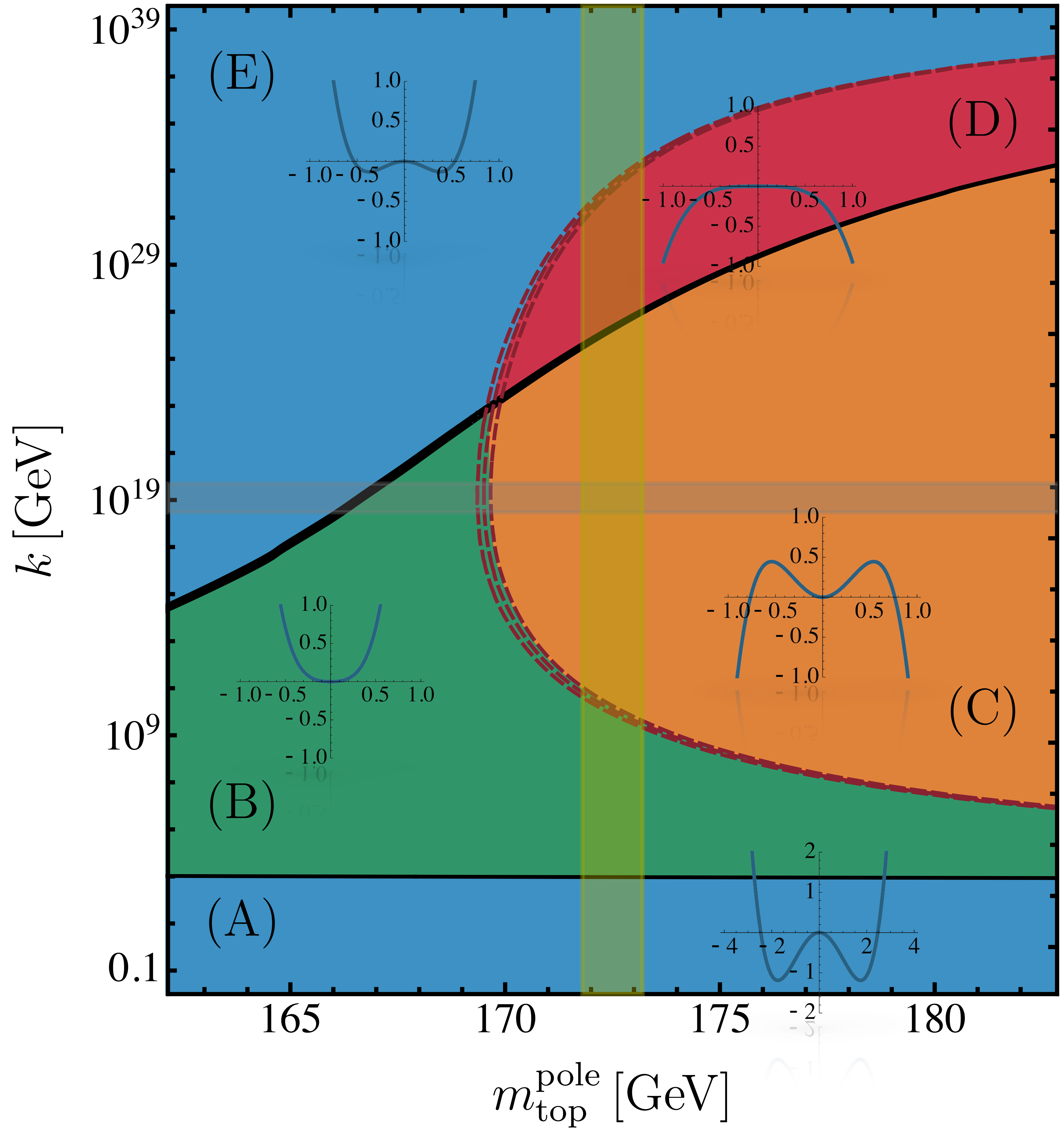


$$y_t^2(k)\big|_{k_{\mathrm{cross}}} \simeq \left[\frac{3}{40}\left[g_1^2(k) + 5\,g_2^2(k)\right] + \bar\lambda(k)\right]\Big|_{k_{\mathrm{cross}}}$$

SM phase diagram

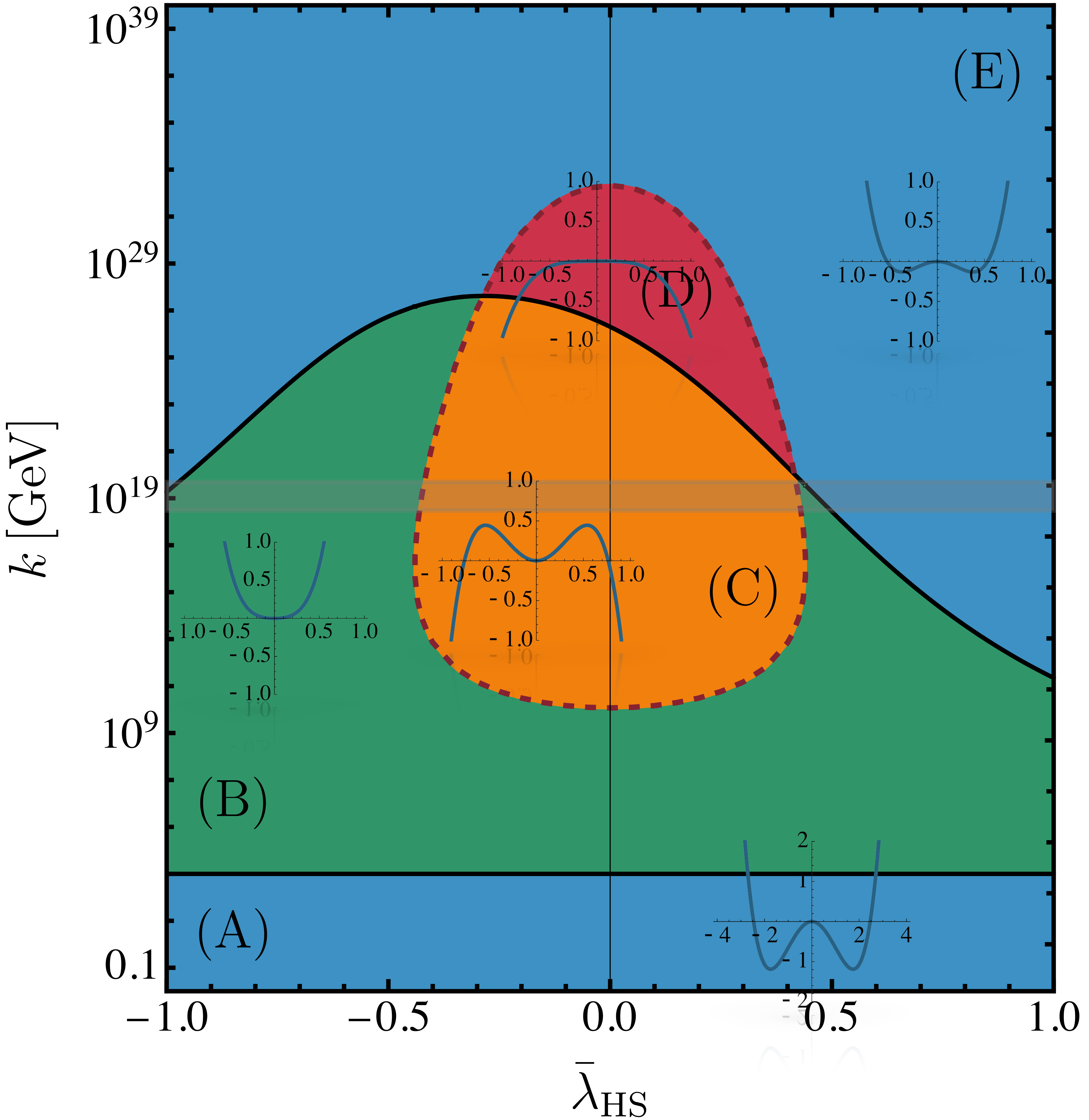


BSM phase diagram

Higgs portal

$$\Delta u(\bar{\rho}, \bar{\rho}_{\rm S}) = \bar{\lambda}_{\rm HS}\, \bar{\rho}\, \bar{\rho}_{\rm S}$$

$$\bar{\rho}_{\rm S} = Z_S\, S^2/2$$



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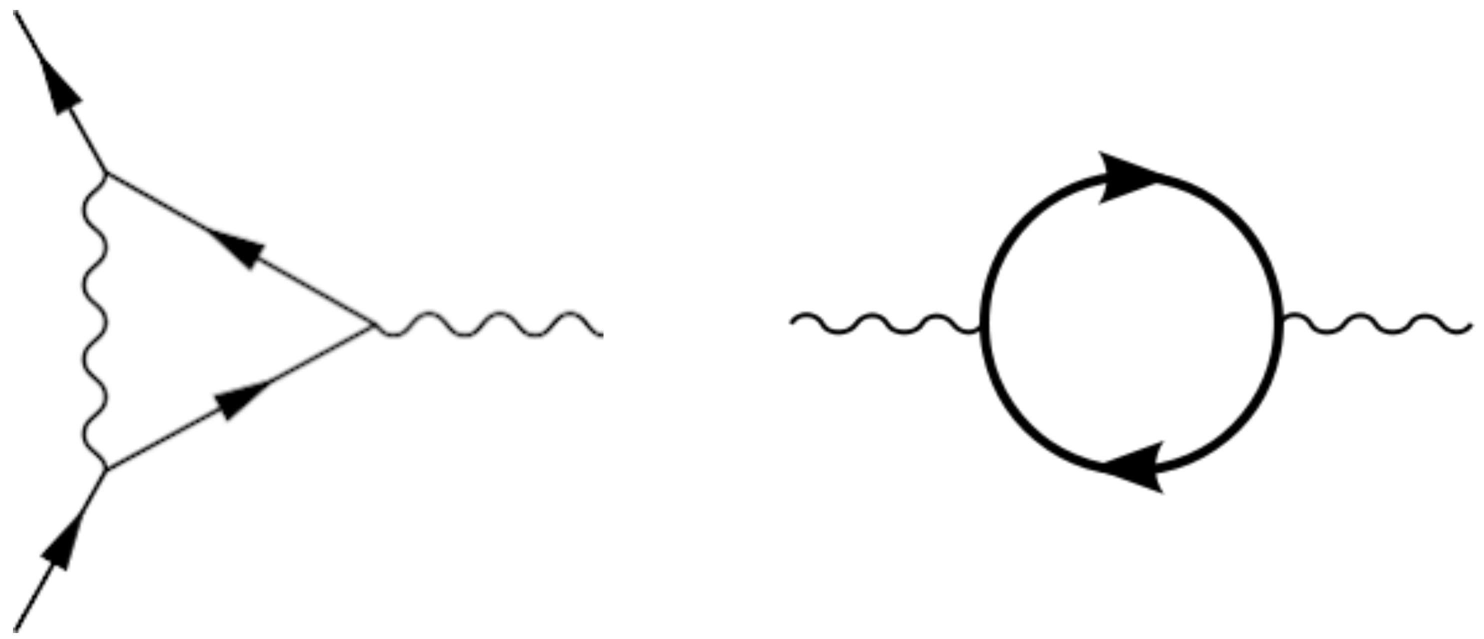
Towards a fundamental SM

- UV completition of stable trajectories
- **Cure** the Abelian Landau pole



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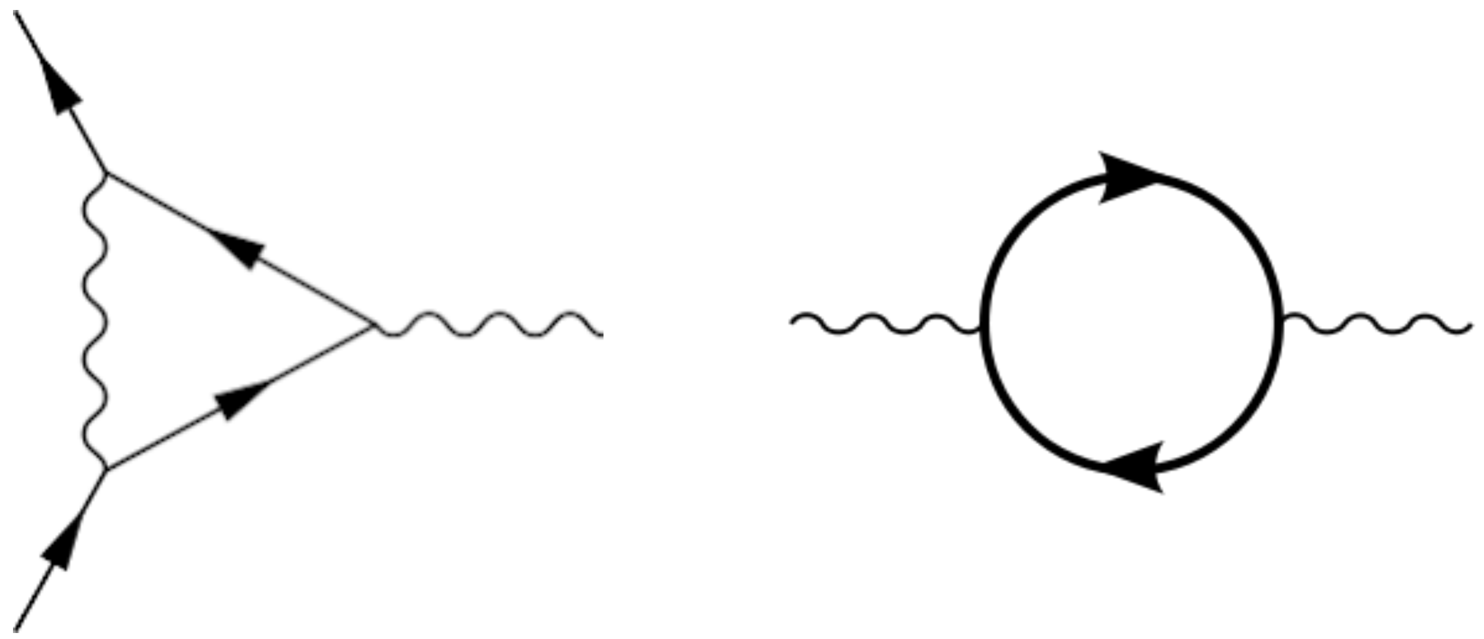

- **Decoupling** of all **charged fermions** in the **new UV broken phase**:

$$m_{\psi_i} > k$$

- **UV fixed-point** condition:

$$\bar{v}^* y_i^* / \sqrt{2} > 1$$

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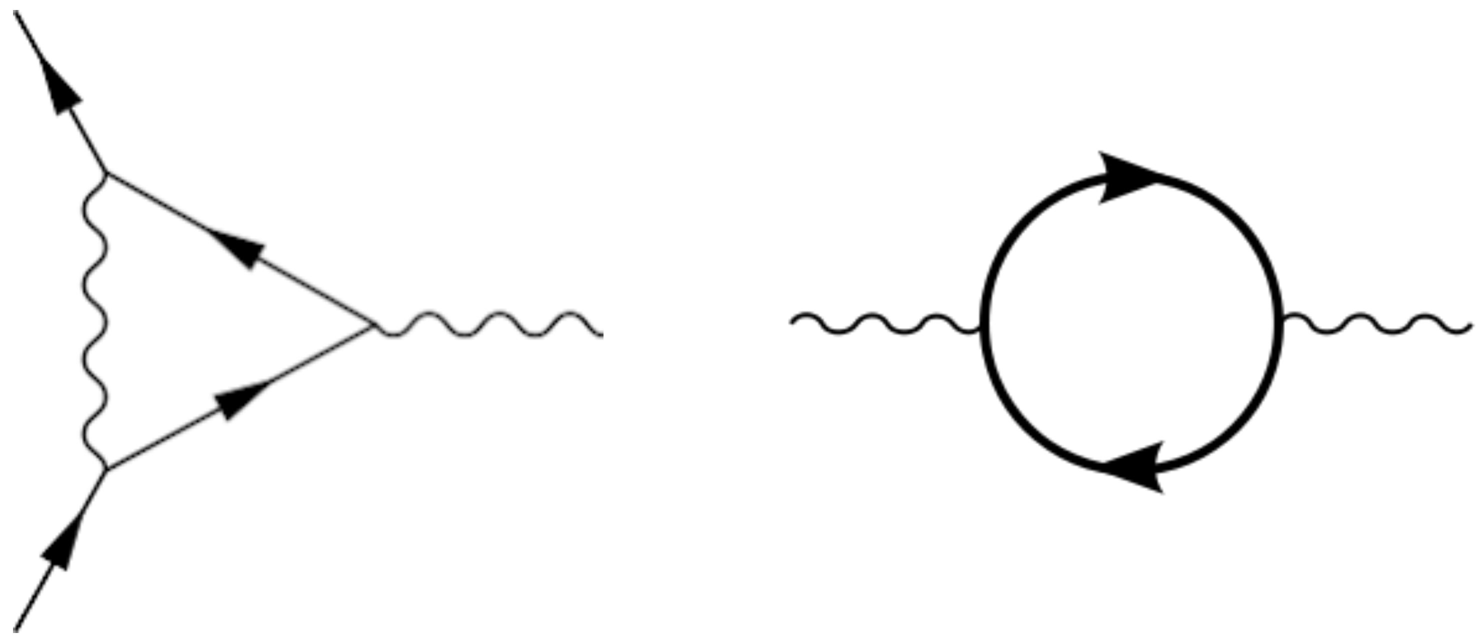

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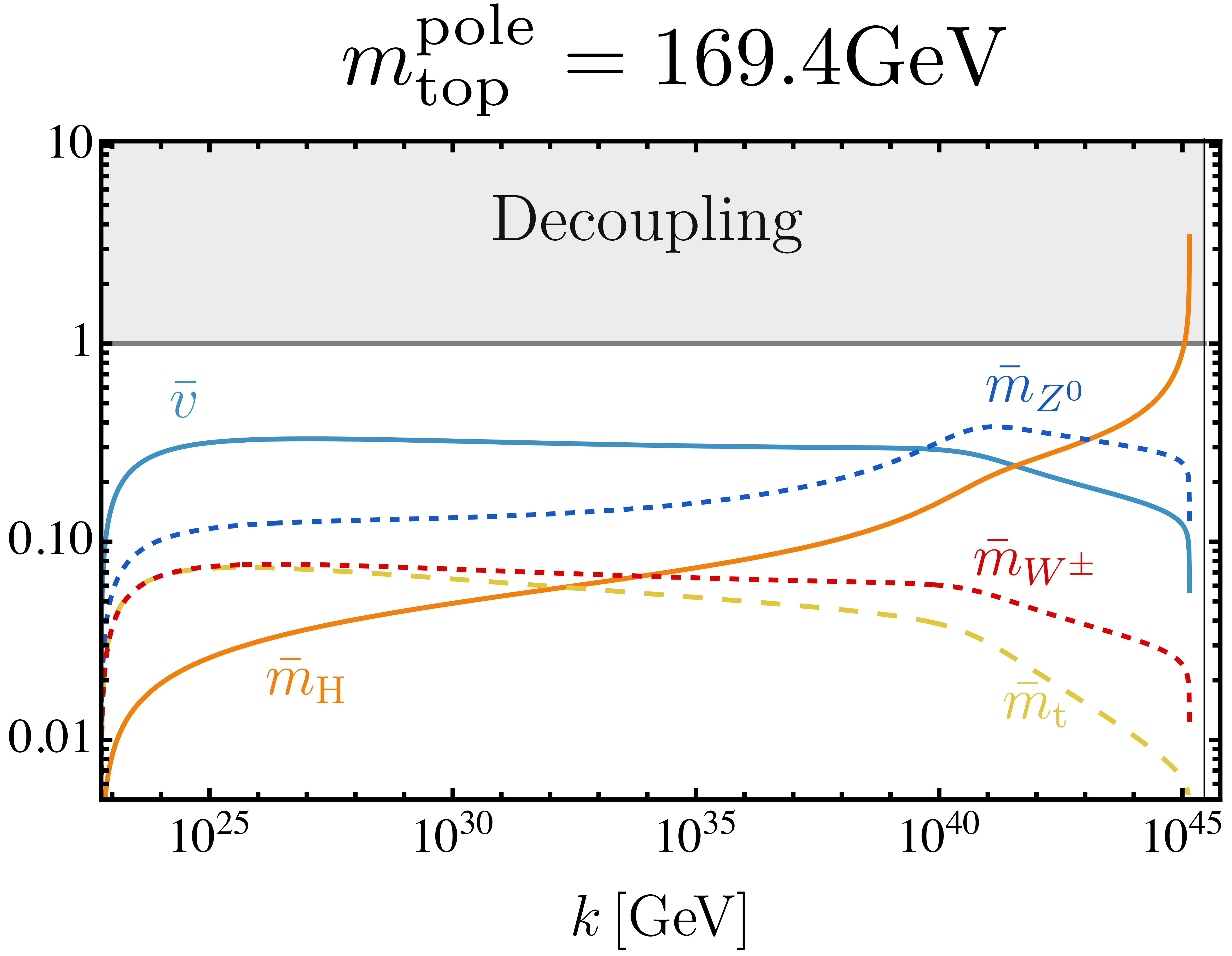

Conclusions

“When you change the way you look at things, the things you look at change”

- Found **two** previously unknown **phases**: an **unstable** and a **stable with a non-trivial minimum.**
  - **Unstable phase:** potentially **invalidate** the SM trajectory at higher energy scales and signals the **need for new physics**.
  - **Non-trivially stable UV phase:** potential **UV-completition** for stable SM-like theories.
  - Potential **existence of further minima** unresolvable in the current polynomial expansion.
- Studied the **SM phase diagram** as a function of the **top quark pole** masses and considering **new physics** in the form of a Higgs-scalar portal coupling.
  - UV non-trivially stable phase appears **below the Planck scale** in scenarios seeking stable trajectories.
  - **Great impact on existing approaches** to new physics and suppose a new look at the high-energy structure of the SM.

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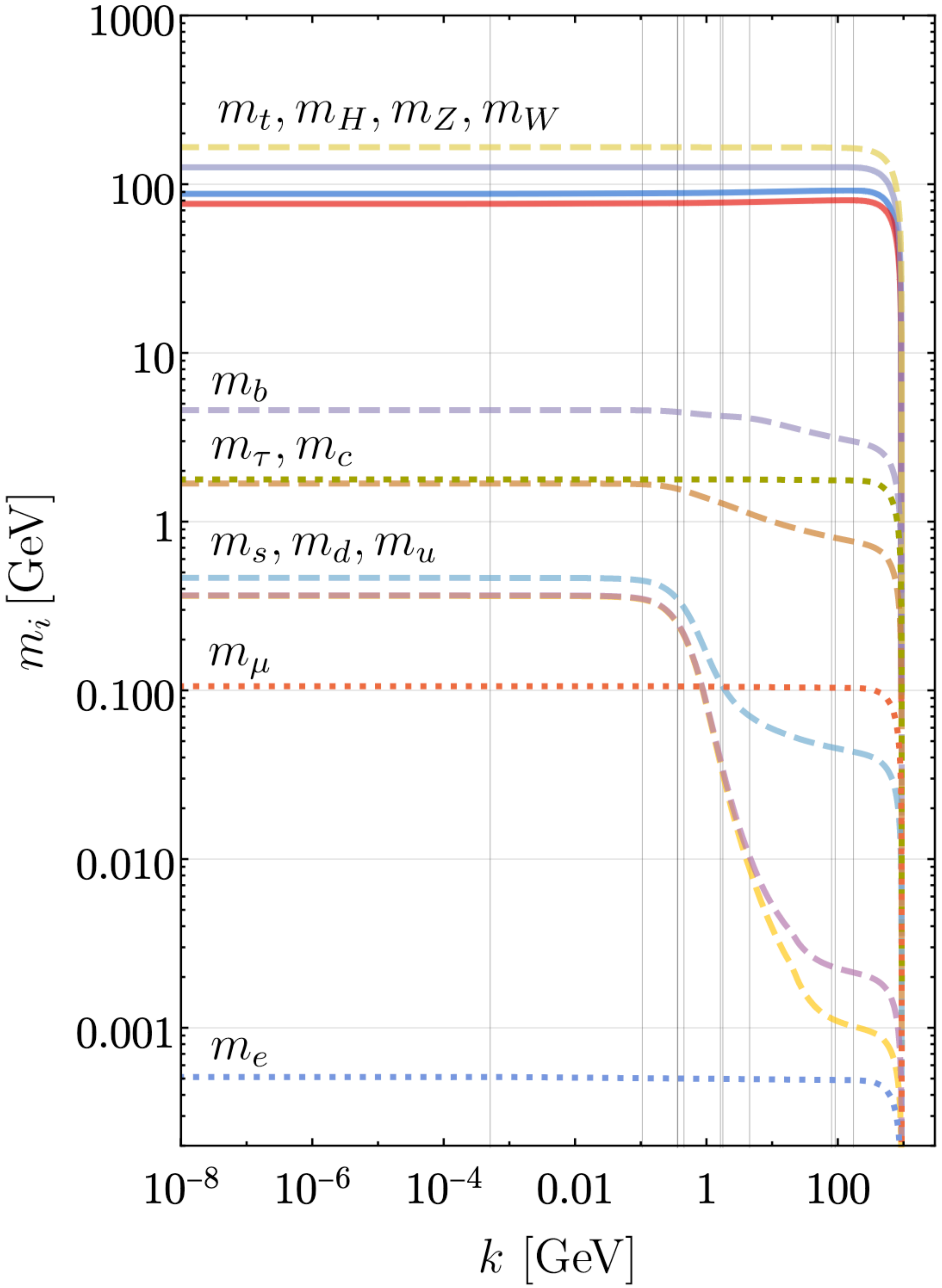
Thank you for your attention!

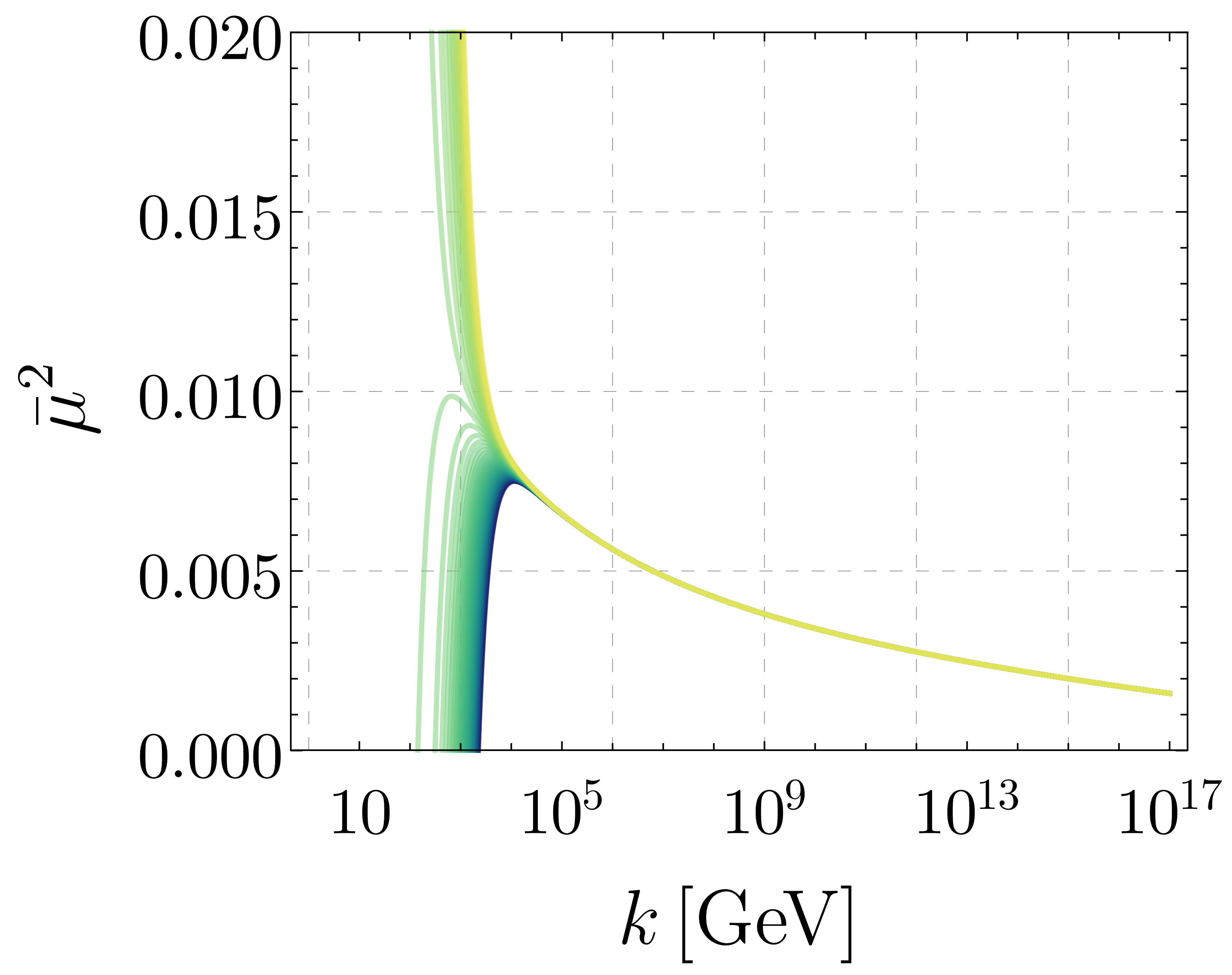
Broken phase flows and euclidean masses

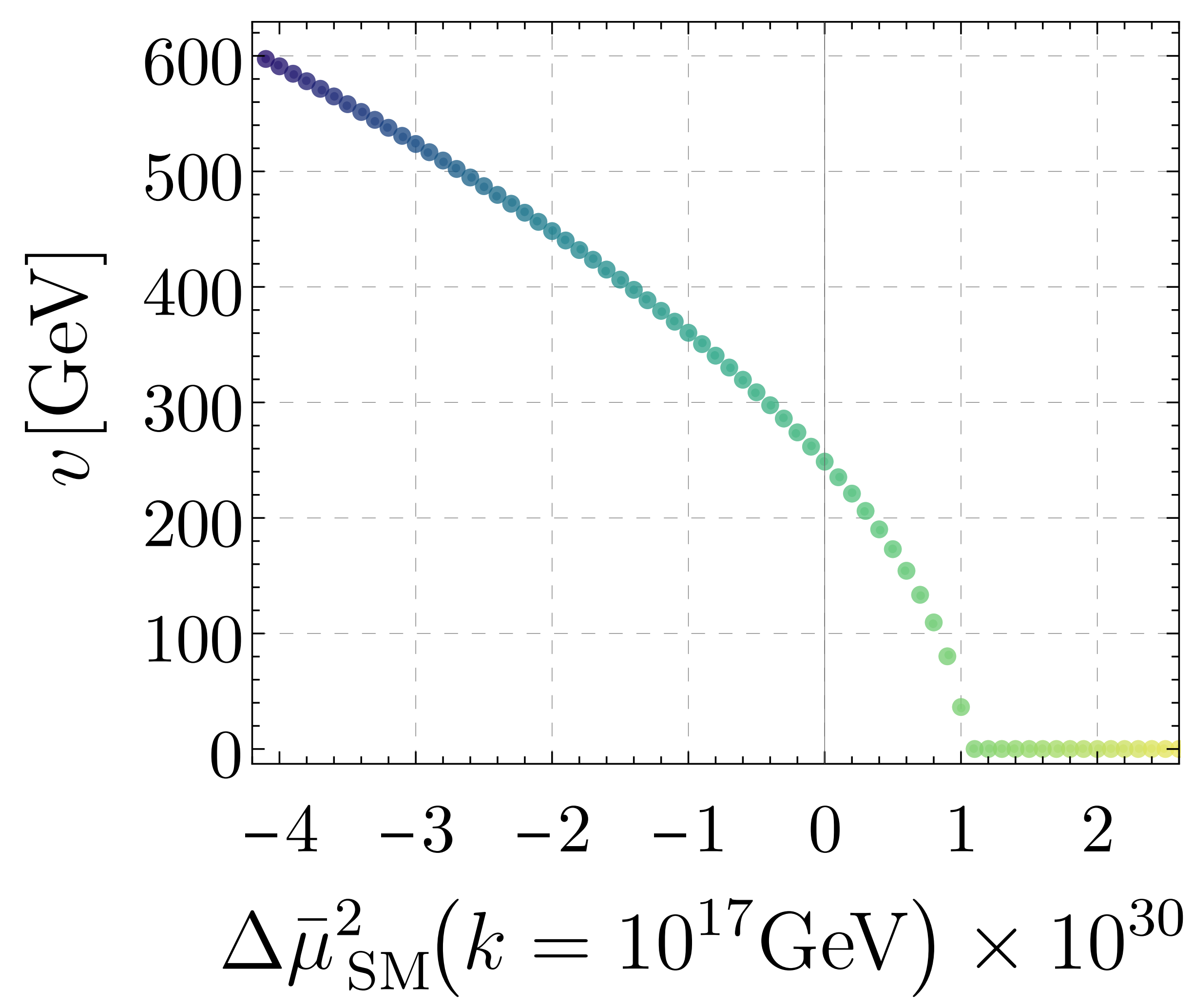


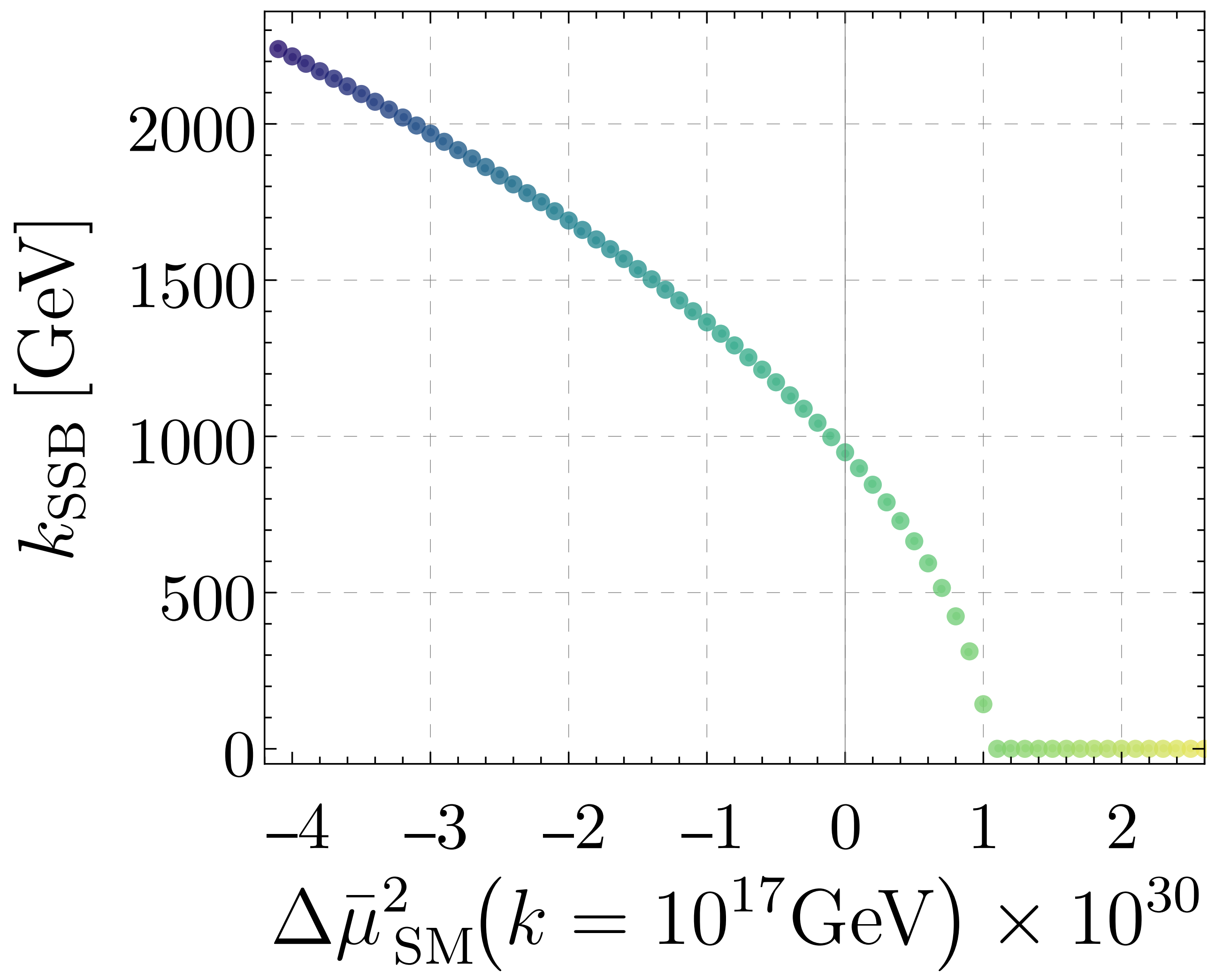
See APG,Pawlowski,Reichert'22:

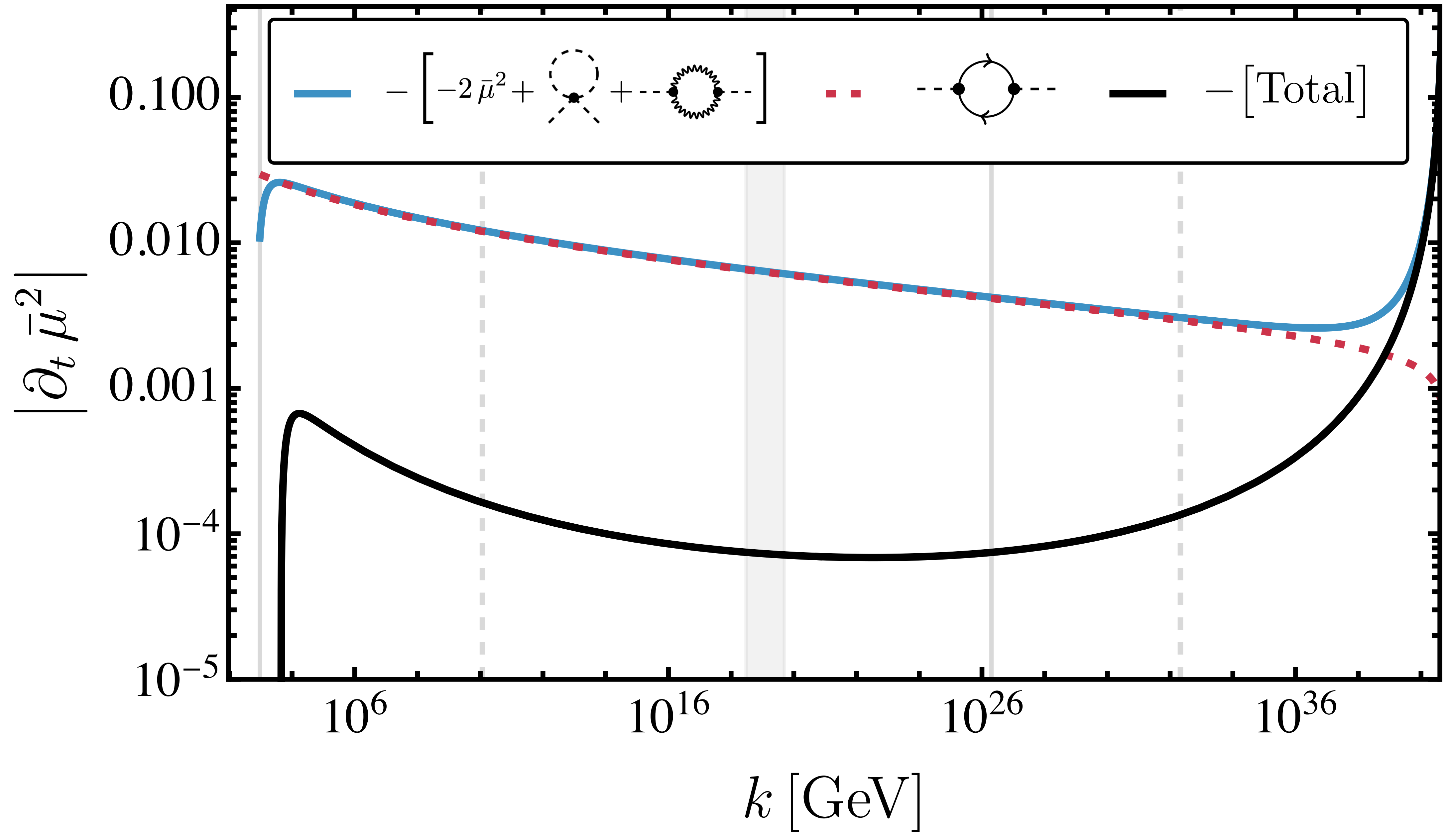
- Accurate implementation of all SM sectors
- Inclusion of deep IR QCD (χSB)
- Top quark pole determination

EWSB





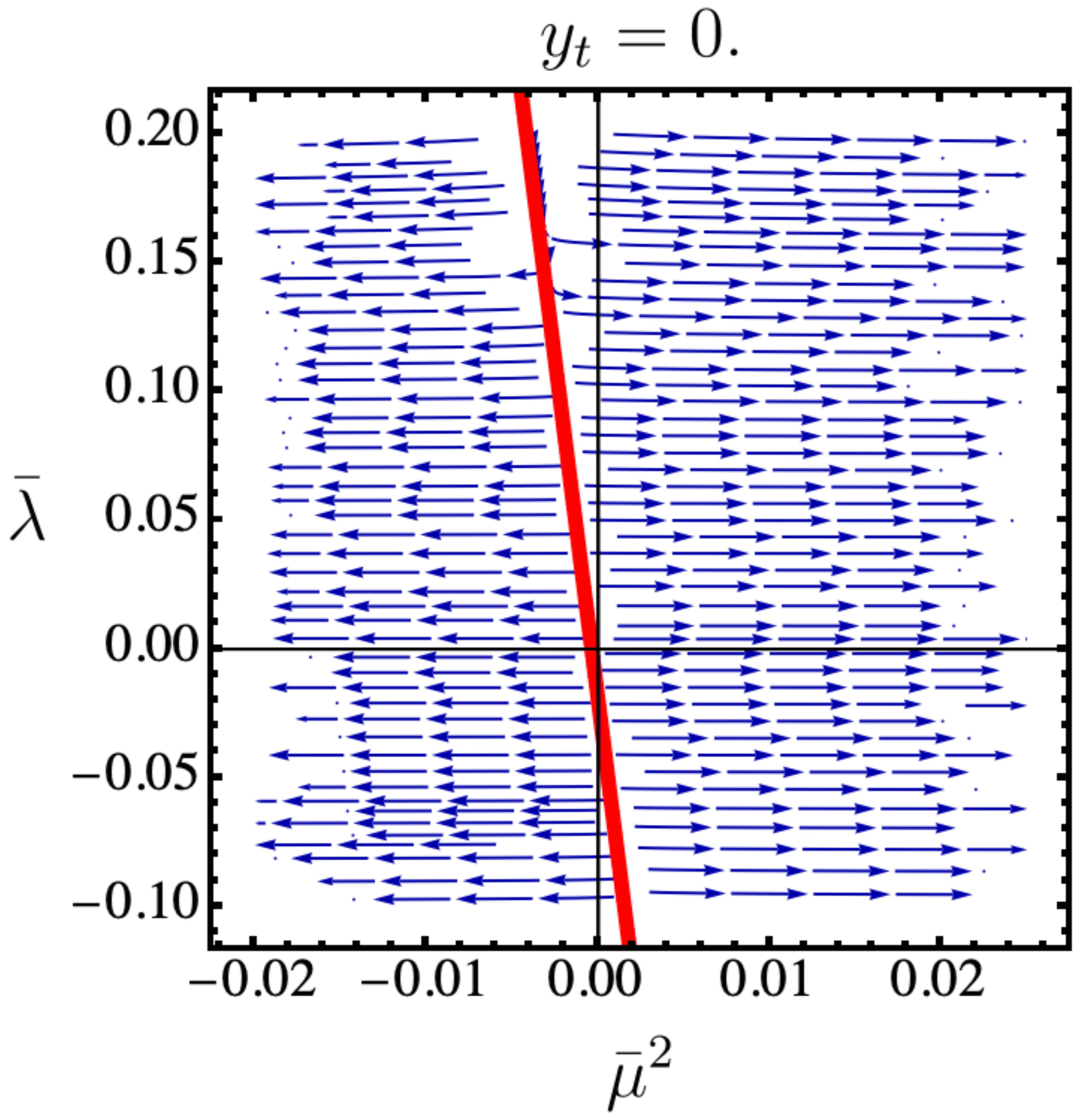


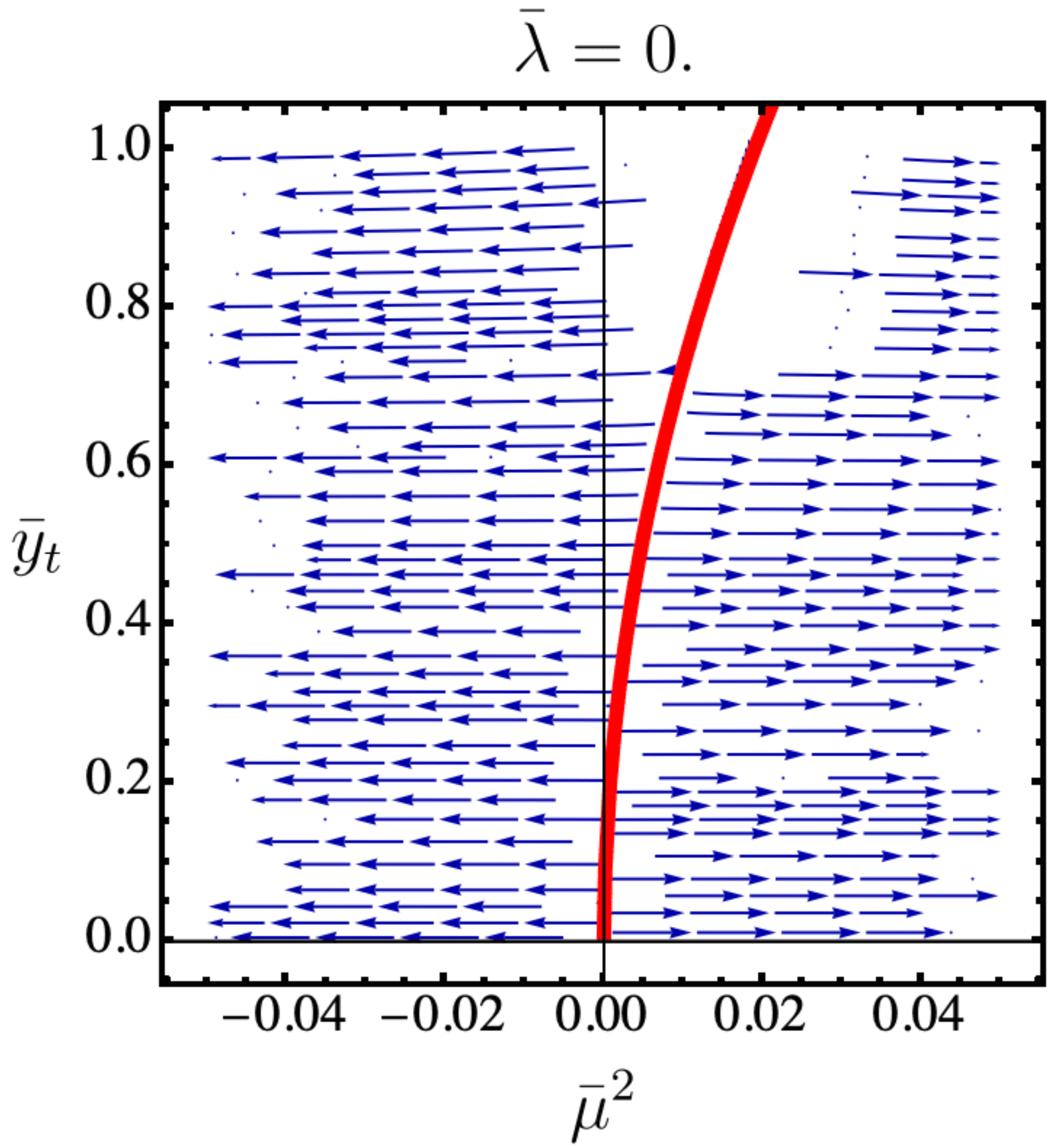


$$\partial_t\,\bar{\mu}^2 = \partial_t\left(\partial_{\bar{\rho}}u(\bar{\rho})\right) = \left(-2+\eta_\Phi\right)\bar{\mu}^2 + \partial_{\bar{\rho}}\,\overline{\rm Flow}\,[V_{\rm eff}]$$

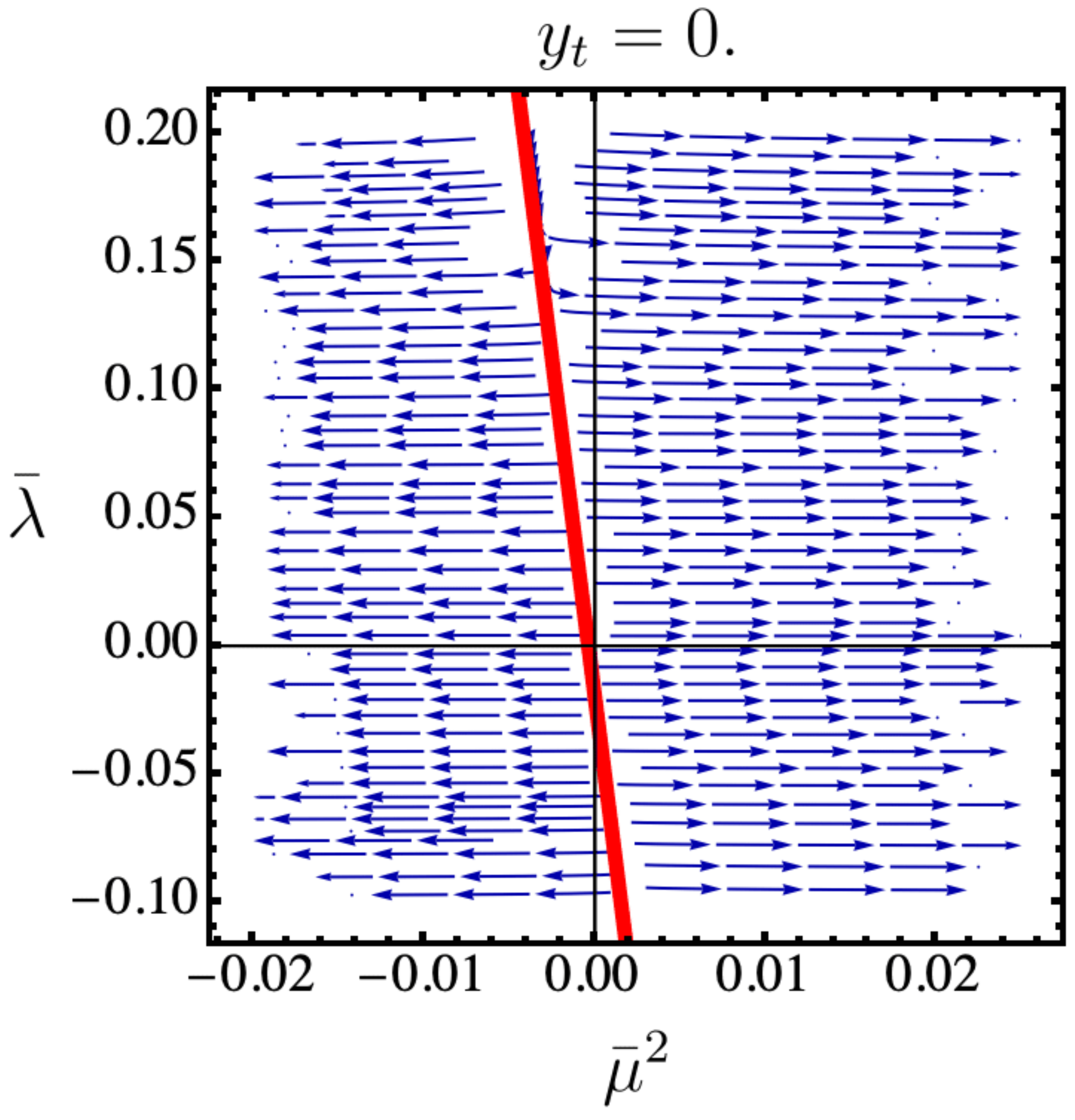
$$\partial_{\bar{\rho}}\,\overline{\rm Flow}\,[V_{\rm eff}] \supset \frac{3\,y_t^2}{8\,\pi^2} - \frac{9\left(g_1^2+5\,g_2^2\right)}{320\,\pi^2} - \frac{3\bar{\lambda}}{8\,\pi^2(1+\bar{\mu}^2)}$$

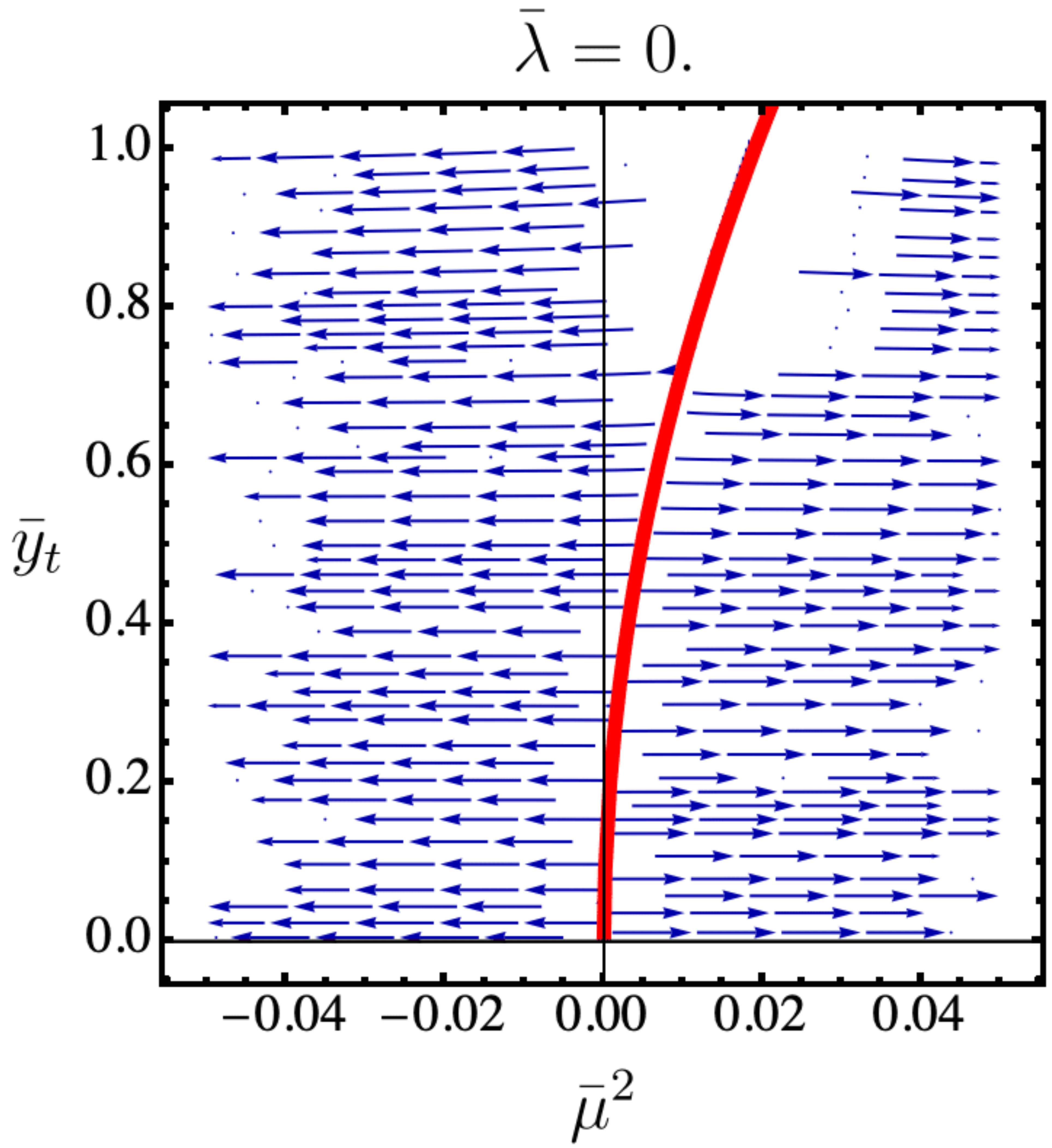
Predicting the EW scale?



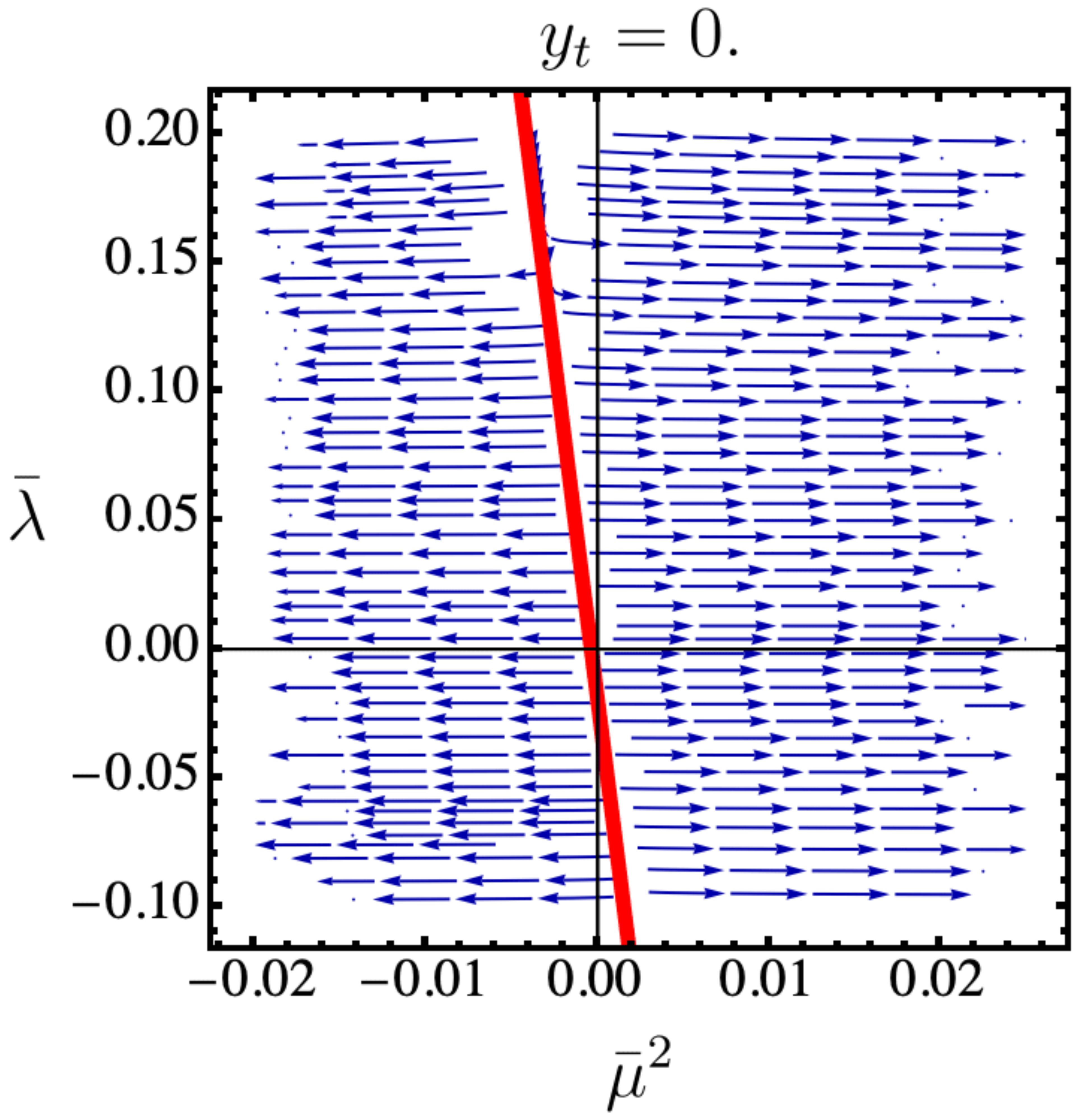


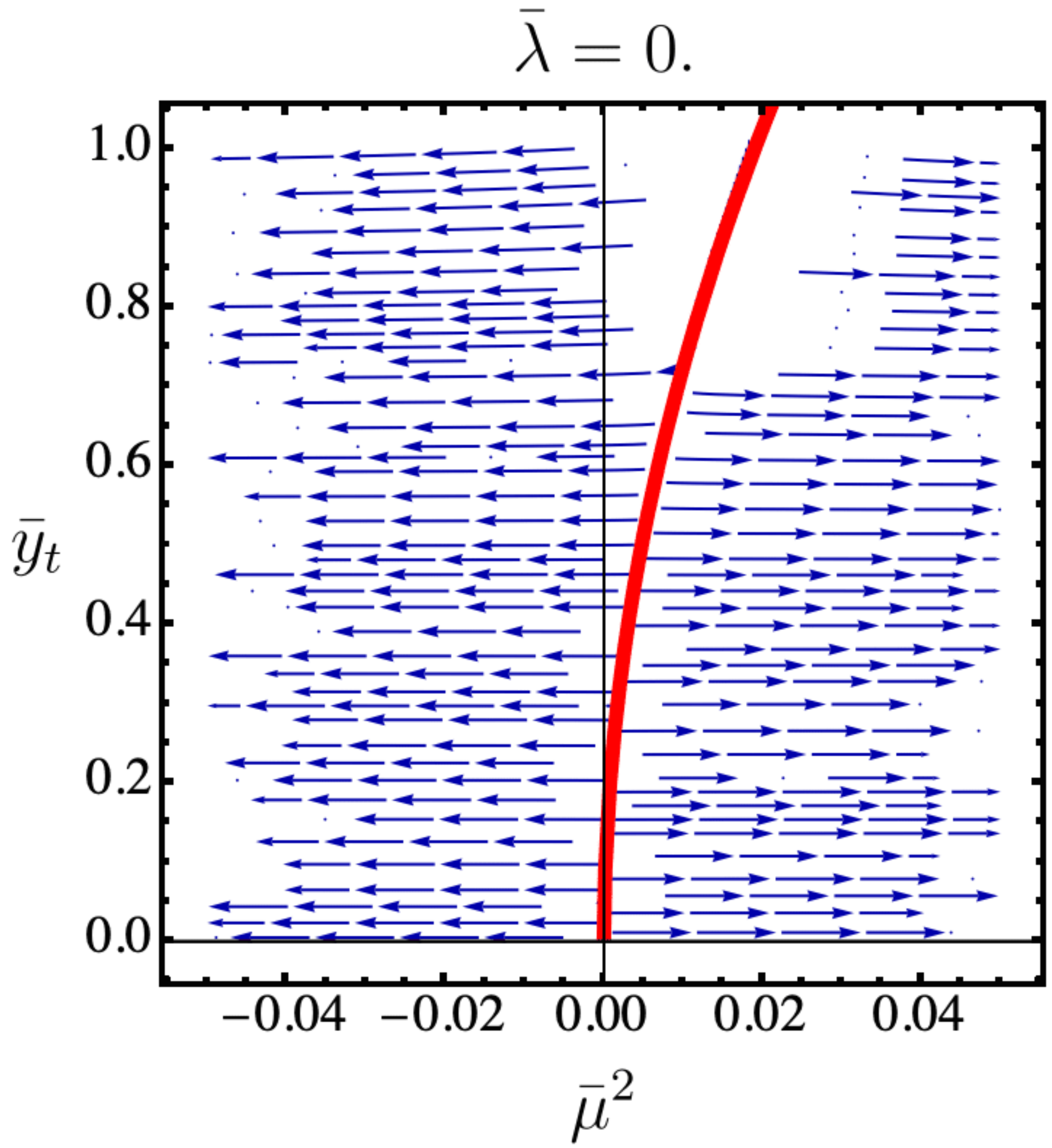
Predicting the EW scale?



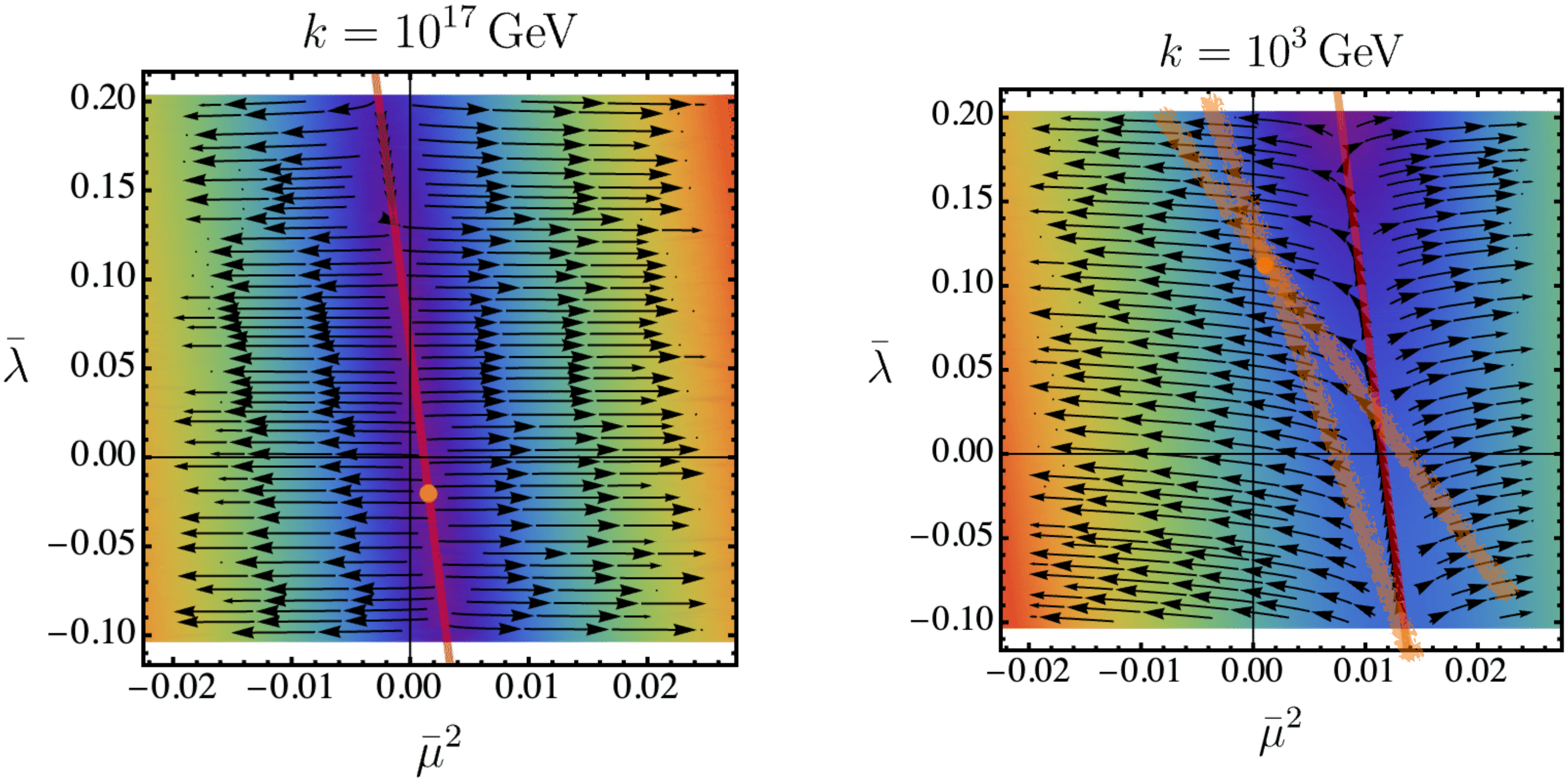


Predicting the EW scale?





Predicting the EW scale?



Predicting the EW scale?